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# DESIGN OF A 3-STATE RECONFIGURABLE CRLH TRANSMISSION LINE BASED ON MEMS SWITCHES

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**Abstract**—Based on the use of micro electro-mechanical system (MEMS) switches this paper presents a composite right/left-handed (CRLH) transmission line (TL) with a reconfigurable behaviour. The design strategy here adopted consists on the use of metal-insulator-metal (MIM) capacitors and short-circuited stubs resulting in a very compact and monolithic CRLH unit cell well suited for phase shifter applications.

## 1. INTRODUCTION

Based on the transmission line (TL) representation of a double negative (DNG) medium, a composite right/left-handed (CRLH) transmission line consists of a host TL periodically loaded with an L-C network in high-pass topology [1–6]. With respect to the implementation of a DNG medium proposed by Smith [7], this 'dual transmission line' approach results in a broadband DNG behaviour, since it does not depend on resonant particles. Furthermore, a CRLH TL can be realized by using standard PCB techniques, this enabling the exploitation of the DNG medium properties in the design of microwave (MW) circuits. Accordingly, in the last years several applications have been proposed demonstrating that the use of CRLH TLs in place of conventional TLs allows improving the performance of common MW devices.

By using micro electro-mechanical system (MEMS) switches, in this paper, we propose a reconfigurable CRLH TL. The proposed design strategy is based on the use of series metal-insulator-metal (MIM) capacitors and shunt short-circuited stubs. This leads to a very

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compact and monolithic unit cell in which the advantages of MEMS technology combine with those corresponding to the CRLH approach.

With respect to different commonly adopted technological solutions (PIN diodes or FET switches) [8–12], the use of MEMS switches in order to achieve a reconfigurable behaviour results in a lower loss, wider band performance, and a lower DC power consumption [13–22]. Furthermore, the advantages related to the use of MEMS devices in designing CRLH TLs have been already demonstrated in [20, 21], where a MEMS series capacitor has been used to control a CRLH TL phase shifter. The approach here presented uses MEMS switches to digitally control both the inductance and the capacitance of the unit cell; this way, a CRLH TL with a variable phase shift and a constant equivalent characteristic impedance has been obtained.

Due to the dispersion properties of the CRLH TL, the proposed device exhibits a nearly constant phase on a very large frequency range and a very low group delay, this rendering it well suited to be used as phase shifter for signal processing in radar applications, wideband communication components, and high-precision instrumentation systems.

The paper is structured as follows: first the CRLH technology is briefly described, and then some details concerning the approach here proposed to design a CRLH line with a reconfigurable phase response are given. Later on, results obtained for a 3-state CRLH line to be used as phase shifter are given and discussed.

## 2. COMPOSITE RIGHT/LEFT-HANDED TRANSMISSION LINE

A CRLH TL is a periodic network whose unit cell consists of a TL of length $2d$, loaded with an $L$-$C$ network in high-pass topology (see Fig. 1). Providing that the phase shift corresponding to the unit cell is negligible with respect to $2\pi$, the line acts as an effectively homogeneous TL with a characteristic impedance ($Z_{CRLH}$) and phase propagation constant ($\beta_{CRLH}$) given by [1]:

$$Z_{CRLH} = \sqrt{\frac{L'}{C'}}\sqrt{\frac{(\omega^2 L_0 C' - 1)}{(\omega^2 C_0 L' - 1)}},$$

$$\beta_{CRLH} = \sqrt{\omega^2 L_0 C_0 + \frac{1}{\omega^2 L' C'} - \frac{(L_0 C' + L' C_0)}{L' C'}}, \quad \left\{C' = (2d)\, C, L' = (2d)\, L\right\}. \tag{1}$$

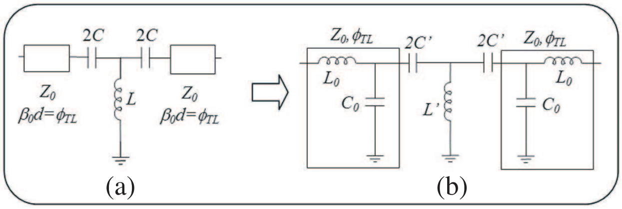



**Figure 1.** (a) Unit cell of a Composite Right/Left-Handed line, (b) corresponding per unit length equivalent circuit ($C' = 2Cd, L' = 2Ld$).

where $L_0$ and $C_0$ are the distributed inductance and capacitance of the loaded TL (see Fig. 1(b)). Eq. (1) evidences the dual nature of the CRLH medium, which under the so-called balanced condition ($\sqrt{L_0 C} = \sqrt{LC_0}$) turns its behaviour from Left-Handed (LH) to Right-Handed (RH) at the frequency:

$$\omega_1 = \frac{1}{\sqrt{L_0 C}} = \frac{1}{\sqrt{LC_0}}. \tag{2}$$

Thanks to its unusual dispersion properties, the CRLH TL technology has attracted widespread interest in recent years [1–6]. For a purely RH TL we have only two degrees of freedom, consequently its parameters are fully determined by imposing a matching condition to an impedance $Z_0$ and a phase delay $\theta_1$ at $\omega_1$. For a balanced CRLH TL, made of $K$ unit cells, in the same conditions assumed for the purely RH TL, we have:

$$\begin{cases} \theta_{CRLH,1} \hat{=} \theta_{CRLH}(\omega_1) = K\left\{-\omega_1\sqrt{L_0 C_0}d + \dfrac{1}{\omega_1\sqrt{LC}}\right\} = \theta_1 \\ Z_{RH} = Z_{LH} = Z_0 \Rightarrow \sqrt{L_0/C_0} = \sqrt{L/C} = Z_0 \end{cases}. \tag{3}$$

From Eq. (3), it is evident that one more degree of freedom is available which can be used to improve the performance of microwave components. Specifically it has been demonstrated that it can be exploited to obtain a dual-band behaviour [1, 3].

Alternatively, this degree of freedom can be fixed to enhance the bandwidth of a microwave component by using a CRLH line with a phase shift $\theta_{CRLH}$ in place of a conventional RH TL with a phase shift $\theta_{RH}$, provided that the condition $|\theta_{CRLH}| < |\theta_{RH}|$ is satisfied [1, 2, 4].

This property has been exploited in [4], where a broadband monodimensional phase shifter has been proposed using printed TLs loaded with lumped element capacitors and inductors in high-pass topology.

In this paper, we suggest a distributed design approach for the CRLH line combined with MEMS resistive switches to achieve a variable phase shift and a constant equivalent characteristic impedance. It is demonstrated that the frequency response of the CRLH TL can be tailored to have a broadband behaviour: a relative bandwidth larger than 7% is obtained. The adopted technology also guarantees very compact devices, with an area of few square millimeters for a 3-state CRLH line working at 1.8 GHz.

In the following sections, more details about the design of the reconfigurable CRLH line will be given and its use as phase shifter suggested.

## 3. M-STATE PHASE-RECONFIGURABLE CRLH TL

Figure 2 shows the schematic of the proposed phase-reconfigurable CRLH TL: it consists of two unit cells which have been designed to have $M$ possible values of $C_{TOT}$ and $L_{TOT}$.

Specifically, each capacitor has been designed by using $N$ shunt branches, each made of a MEMS switch in series with a MIM capacitor; this way, referring to Fig. 2, the discrete values of $C_{TOT}$ are given by:

$$C_{TOT,j}=\sum_{i=1}^{N}(1-p_i)\left(\frac{1}{C_{up}}+\frac{1}{C_{MIM,i}}\right)^{-1}+\sum_{i=1}^{N}p_i\left(\frac{1}{C_{down}}+\frac{1}{C_{MIM,i}}\right)^{-1} \quad (4)$$

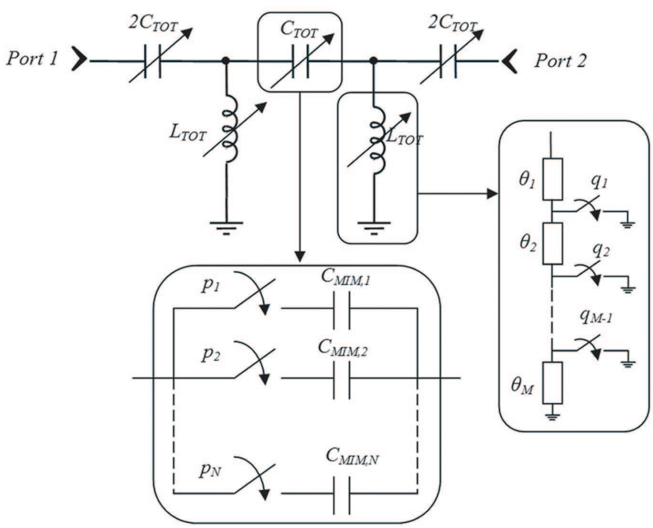



**Figure 2.** Schematic of the proposed $M$-state CRLH line.

where $p_i$ is a binary quantity related to the state of the switch $i$:

$$p_i = \begin{cases} 1, \text{ if switch } i \text{ down} \\ 0, \text{ if switch } i \text{ up} \end{cases}, \quad i \in [1, N] \tag{5}$$

whilst $C_{up}$ and $C_{down}$ are respectively the MEMS switch capacitance in the up and in the down state. From Eqs. (4) and (5) it can be derived that, depending on the relative state of the $N$ switches, the useful values of $C_{TOT}$ are:

- $M = 2^N$ when capacitive switches are adopted,
- $M = (2^N - 1)$ when resistive switches with a negligible value of $C_{up}$ are adopted.

As far as it concerns the variable inductor, a short-circuited stub of variable length has been employed. Referring to Fig. 2, by using $(M-1)$ MEMS switches in a shunt configuration, $M$ values of $L_{TOT}$ are possible:

$$L_{TOT,j} = \frac{Z_0 \text{tg}\left(\theta_{TOT}\right)}{\omega} = \frac{Z_0}{\omega}\text{tg}\left(\theta_{MAX} - \sum_{i=1}^{(M-1)} q_i \theta_{i+1}\right) \Rightarrow \left[L_{TOT,j}\right]_{j=1}^{M}$$

$$\left\{\theta_{MAX} = \sum_{i=1}^{M} \theta_i\right\}, \; q_i = \begin{cases} 1, \text{ if switch } i \text{ down} \\ 0, \text{ if switch } i \text{ up} \end{cases}, \quad i \in [1, M-1] \tag{6}$$

According to Eq. (3), by using the circuit schematic of Fig. 2, in order to achieve $M$ different values of the line phase shift ($\theta_{CRLH,j}$) corresponding to the same equivalent characteristic impedance $L_{TOT},_j$ and $C_{TOT,j}$ must be fixed as follows:

$$\begin{cases} K\left[-\left(\omega\sqrt{L_{0j}C_{0j}}\right) + \frac{1}{\left(\omega\sqrt{L_{TOT,j}C_{TOT,j}}\right)}\right] \approx \frac{K}{\left(\omega\sqrt{L_{TOT,j}C_{TOT,j}}\right)} = \theta_{CRLH,j} \\ \sqrt{\frac{L_{TOT,j}}{C_{TOT,j}}} = Z_{CRLH} \end{cases}$$

$$\Rightarrow \begin{cases} C_{TOT,j} = \left(\dfrac{K}{\omega\theta_{CRLH,j}}\right)^2 \dfrac{1}{L_{TOT,j}} \\ \left(\dfrac{\omega\theta_{CRLH,j}}{K}\right) L_{TOT,j} = Z_{CRLH} \end{cases}$$

$$\Rightarrow \begin{cases} C_{TOT,j} = \left(\dfrac{K}{\omega\theta_{CRLH,j}}\right) \dfrac{1}{Z_{CRLH}} \\ L_{TOT,j} = Z_{CRLH} \dfrac{K}{\omega\theta_{CRLH,j}} \end{cases}, \qquad j \in [1, M] \tag{7}$$

where $K$ is the number of CRLH unit cells, and it has been assumed that the RH contribution to $\theta_{CRLH,j}$ can be neglected at the working frequency.

In the next section, results obtained by fixing $N = K = 2$ and $M = 3$ will be given and discussed; it will be showed that the proposed design approach joins three useful characteristics: very compact dimensions, broadband phase responses and small values of the insertion loss.

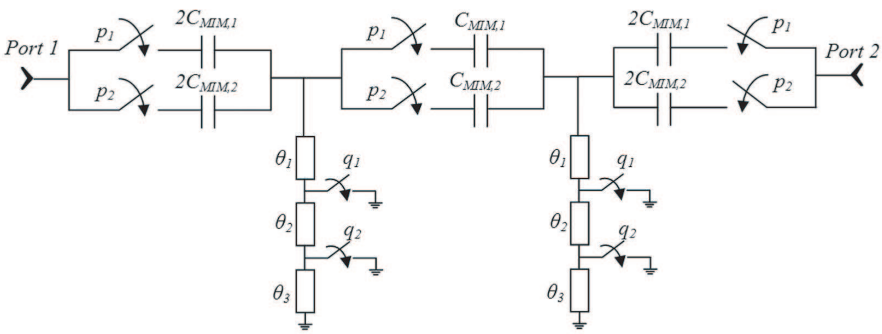



**Figure 3.** Schematic of the 3-state CRLH line.

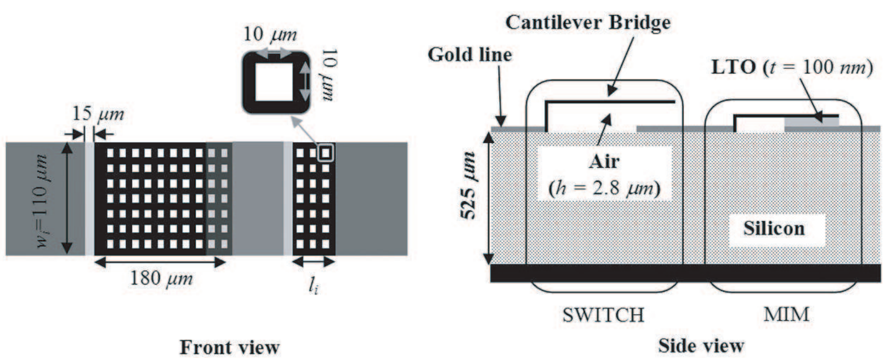



**Figure 4.** Layout of the series between the MEMS resistive switch and the MIM capacitor.

## 4. 3-STATE PHASE SHIFTER DESIGN AND RESULTS

Figure 3 illustrates the schematic of a reconfigurable CRLH line to be used as 3-state phase shifter; 2 unit cells have been used. Each capacitor consists of 2 shunt branches made of a series resistive MEMS switch and a MIM capacitor (see Figs. 3 and 4). As for the short-circuited stubs, they have been designed with a variable length by means of 2 resistive air-bridge MEMS switches in a shunt configuration (see Figs. 3 and 5). The selected working frequency is 1.8 GHz.

The design process started with the circuital optimization of the schematics corresponding to the useful combinations of the switches. This has been done by modeling the MEMS devices as ideal switches (i.e., by replacing them with open-circuits in the up state and with short-circuits in the down state). It is worth observing that, due to the adoption of resistive switches in designing $C_{TOT}$ ($\Rightarrow C_{up} \approx 0$), the CRLH line is equivalent to an open circuit when both series switches are in the off-state, so that three are the useful combinations of these switches. Consequently, three are the schematics which have been optimized (the corresponding parameters are summarized in Table 1). The following goals were adopted: required line phase shift at 1.8 GHz respectively equal to 30°, 45°, 90°, and characteristic impedance equal to 50 Ω. The optimum circuit parameters resulting in the desired line

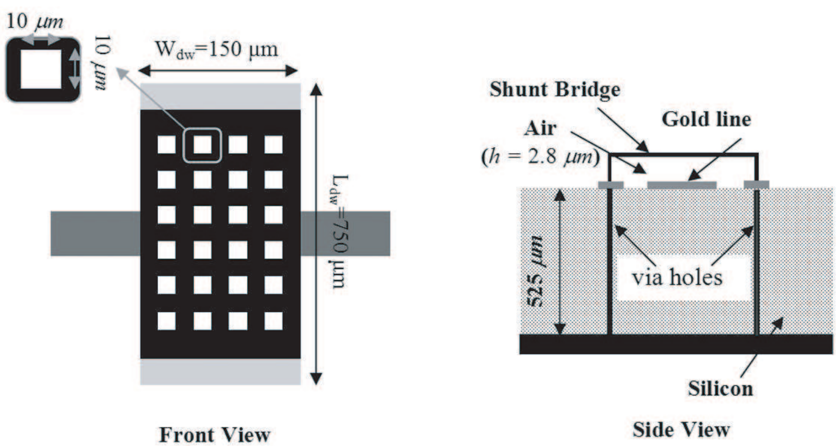



**Figure 5.** Layout of the shunt ohmic-contact MEMS air-bridge switch.

**Table 1.** Parameters of the three circuit schematics optimized in order to design the CRLH line as a 3-state phase shifter.

| **State 1 - Schematic 1** | **Optimization goals** |
|---|---|
| Switch $p_1$ and $p_2$ on<br>$\Rightarrow (p_1 = 1, p_2 = 1)$<br>$\Rightarrow C_{TOT,1} = (C_{MIM,1} + C_{MIM,2})$ | $\theta_{CRLH} = 30°@\,1.8\,\text{GHz}$<br>$Z_{CRLH} = 50\,\Omega$ |
| Switch $q_1$ and $q_2$ on<br>$\Rightarrow (q_1 = 0, q_2 = 0)$<br>$\Rightarrow L_{TOT,1} = \frac{Z_0 \text{tg}(\theta_1+\theta_2+\theta_3)}{\omega}$ | |
| **State 2 - Schematic 2** | **Optimization goals** |
| Switch $p_1$ off and Switch $p_2$ on<br>$\Rightarrow (p_1 = 0, p_2 = 1)$<br>$\Rightarrow C_{TOT,2} = C_{MIM,2}$ | $\theta_{CRLH} = 45°@\,1.8\,\text{GHz}$<br>$Z_{CRLH} = 50\,\Omega$ |
| Switch $q_1$ on and Switch $q_2$ off<br>$\Rightarrow (q_1 = 0, q_2 = 1)$<br>$\Rightarrow L_{TOT,2} = \frac{Z_0 \text{tg}(\theta_1+\theta_2)}{\omega}$ | |
| **State 3 - Schematic 3** | **Optimization goals** |
| Switch $p_1$ on and Switch $p_2$ off<br>$\Rightarrow (p_1 = 1, p_2 = 0)$<br>$\Rightarrow C_{TOT,3} = C_{MIM,1}$ | $\theta_{CRLH} = 90°@\,1.8\,\text{GHz}$<br>$Z_{CRLH} = 50\,\Omega$ |
| Switch $q_1$ and $q_2$ off<br>$\Rightarrow (q_1 = 1, q_2 = 1)$<br>$\Rightarrow L_{TOT,3} = \frac{Z_0 \text{tg}(\theta_1)}{\omega}$ | |

behaviour were:

$$L_{TOT,1} = 18\,\text{nH},\;\; L_{TOT,2} = 12\,\text{nH},\;\; L_{TOT,3} = 6\,\text{nH}$$
$$C_{TOT,1} = 6\,\text{pF}, C_{TOT,2} = 4\,\text{pF}, C_{TOT,3} = 2\,\text{pF}$$
$$\Rightarrow C_{MIM,1} = 2\,\text{pF}, C_{MIM,2} = 4\,\text{pF} \tag{8}$$

The design process was carried on by converting the circuit schematic of Fig. 3 in microstrip technology on a silicon substrate; the corresponding layout is illustrated in Fig. 6.

The occupied area is equal to $(2.65 \times 5.42)\,\text{mm}^2$; more details about the design of the switches and the MIM capacitors will be given in the following part of the section.

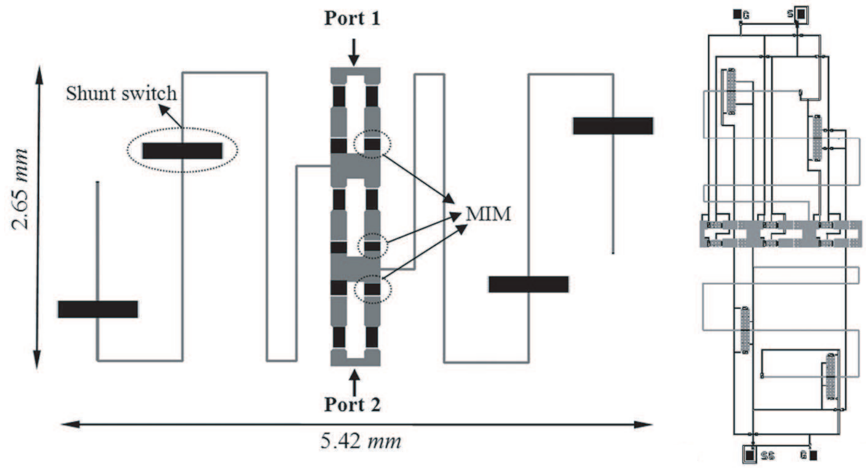



**Figure 6.** Layout of the proposed 3-state CRLH line (a) without and (b) with the switch bias network.

### 4.1. Switch Design and Optimization

Referring to the fabrication process described in [18], MEMS switches have been designed in microstrip technology on a silicon substrate ($h = 525\,\mu\text{m}$) with a gold metallization and a nominal air gap of 2.8 μm.

Specifically, a cantilever topology and an in-line orientation with respect to the microstrip line have been used for the MEMS series resistive switches [13]. In order to have an experimental reference, the thickness, the area, and the shape of the bridge have been fixed as described in [18]. According to the solution suggested in [18], air holes have been used in designing the bridge membrane (see Fig. 4) to achieve a higher flexibility and a reduced damping. Furthermore, in order to guarantee a reduced contact resistance, 7 dimples have been placed in the contact area between the bridge and the microstrip line.

The corresponding layout is illustrated in Fig. 4; referring to the experimental results reported in [18] we expect an actuation voltage of about 50 V and a contact resistance lower than 1 Ω.

As for the MEMS air-bridge switches employed in designing the variable length short-circuited stubs, the layout adopted is illustrated in Fig. 5. Referring to the experimental results reported in [19], the switch dimensions have been fixed in order to have an actuation voltage of about 50 V.

### 4.2. MIM Capacitor Design

The dimensions of the MIM capacitors (see Fig. 4) have been fixed by using the following formula for the associated capacitance [13]:

$$C_{MIM,i} = C_{pp,i} + C_{ff,i} = \frac{130}{100}\left(\frac{\varepsilon_0 \varepsilon_r w_i l_i}{t}\right), \quad i = 1, 2 \tag{9}$$

where $C_{pp,i}$ is the parallel plate capacitance ($w_i l_i$ is the MIM$_i$ plate area), whilst $C_{ff,i}$ is a term due to the fringing field which has been assumed as the 30% of $C_{pp,i}$.

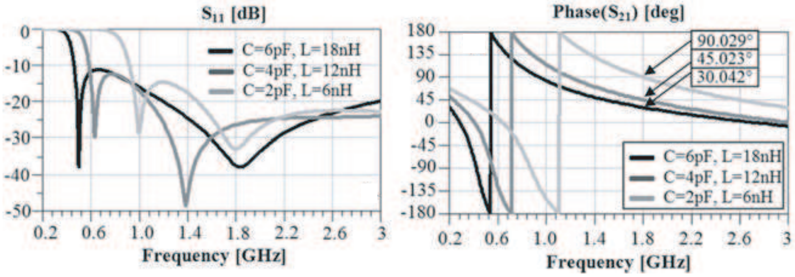
A 100 nm thick low temperature oxide (LTO) has been used as insulator, whilst $w_i$ and $l_i$ have been determined according to Eq. (9) in such a way to have $C_{MIM,1}$ equal to 2 pF and $C_{MIM,2}$ equal to 4 pF.

## 5. 3-STATE PHASE SHIFTER RESULTS

In order to verify the performance of the proposed phase shifter, full-wave simulations have been performed for the layouts corresponding to the three useful combinations of the switches. The corresponding full-wave simulation results are illustrated in Figs. 7 and 8, and resumed in Table 2. Fig. 7(a) shows the phase shifter reflection coefficient

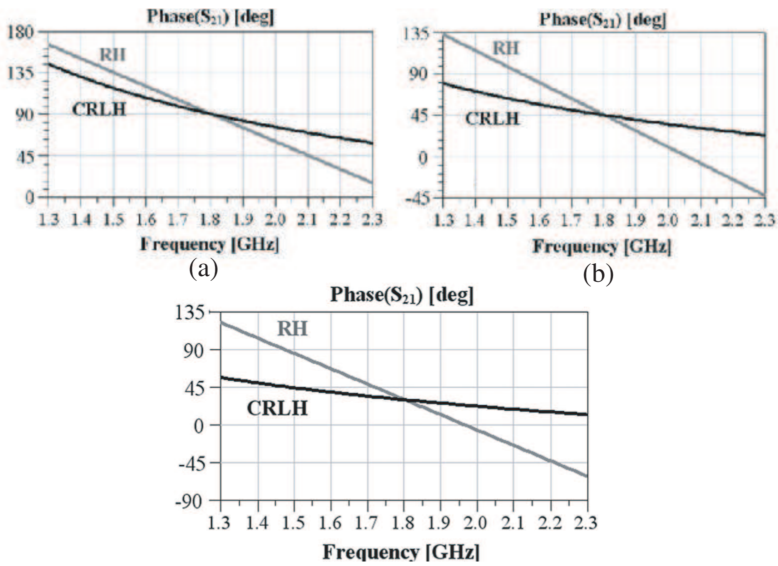
**Table 2.** Results of the full-wave analysis of the 3-state phase shifter.

| | | **State 1** | **State 2** | **State 3** |
|---|---|---|---|---|
| Switch state | $p_1$ | on | off | on |
| | $p_2$ | on | on | off |
| | $q_1$ | on | on | off |
| | $q_2$ | on | off | off |
| Total inductance $L_{TOT}$ | | 18 nH | 12 nH | 6 nH |
| Total capacitance $C_{TOT}$ | | 6 pF | 4 pF | 2 pF |
| Phase ($S_{21}$) [deg] @ 1.8 GHz | | 30.042 | 45.023 | 90.029 |
| $\lvert S_{11}\rvert$ [dB] @ 1.8 GHz | | −37.6 | −26.4 | −33 |
| Relative Bandwidth | Proposed CRLH line | 13.26% | 10.5% | 7.03% |
| | Conventional RH line | 2.99% | 3.16% | 3.71% |




(a) (b)

**Figure 7.** Scattering parameters of the 3-state CRLH line proposed in this paper. (a) Reflection coefficient corresponding to the three useful combinations of the switch states: a normalization impedance equal to 50 Ω has been used. (b) Phase response corresponding to the three states: a phase respectively equal to 30°, 45° and 90° has been obtained.




(c)

**Figure 8.** Comparison between the phase response of the proposed 3-state CRLH TL and the one of a conventional microstrip line designed to have the same phase shift at 1.8 GHz ((a) state 3, (b) state 2, (c) state 1). It is evident that the proposed device exhibits a broader bandwidth.

calculated by using a normalization impedance equal to 50 Ω; an excellent matching has been obtained for all states. Fig. 7(b) shows the phase of the transmission coefficient corresponding to the three states: a phase respectively equal to 30°, 45° and 90° has been obtained.

Figure 8 compares the phase of the CRLH line transmission coefficient with that corresponding to a conventional microstrip line having the same phase shift at $f_0 = 1.8\,\text{GHz}$. It can be noticed that the CRLH line exhibits a very flat phase response resulting in a broader bandwidth.

More specifically, if we define the relative bandwidth as follows:

$$\text{Bandwidth }\% \hat{=} \left(\frac{\Delta f}{f_0}\right) \cdot 100 \tag{10}$$

where $\Delta f$ is the range of frequencies in which the scattering parameters satisfy the following relations:

$$|S_{11}\,(\text{dB})| \leq -20\text{dB},\ \text{phase}\ \ (S_{21}) \in [\theta_{CRLH}\,(f_0) \pm 5°] \tag{11}$$

the relative bandwidths of the proposed phase shifter are:

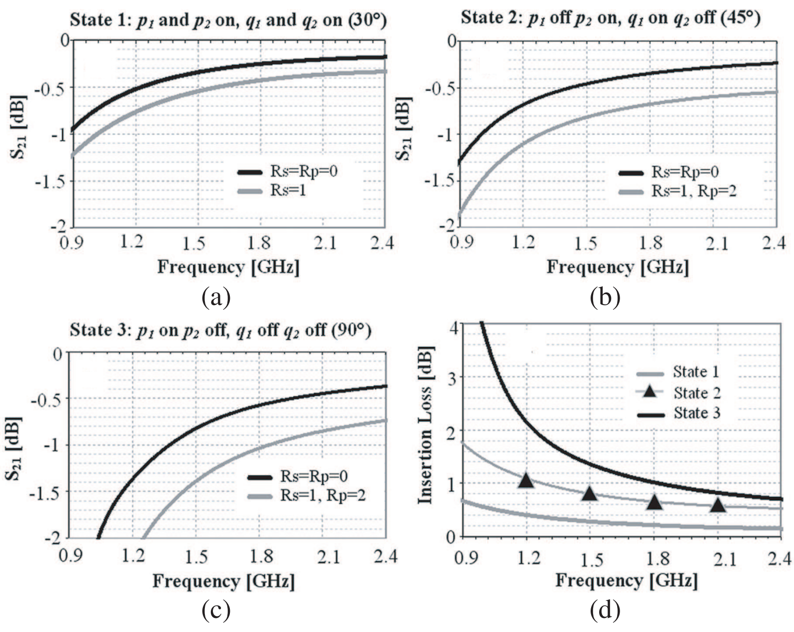



**Figure 9.** Results achieved by combining full-wave simulation in schematic circuit simulation in order to account the effects of the contact resistance associated to the switches in the down state performing. In all states, values of the amplitude of the insertion loss smaller than 1dB have been obtained.

State 1 ($\theta_{CRLH} = 30°$): 13.26%;
State 2 ($\theta_{CRLH} = 45°$): 10.5%;
State 3 ($\theta_{CRLH} = 90°$): 7.03%,

whilst those calculated for a microstrip line are approximatively equal to 3%.

As for the insertion loss corresponding to the three states of the proposed phase shifter, full-wave simulations illustrated in Figs. 7 and 8 have been performed by using a planar simulator based on the Method of the Moments (ADS-Momentum). Consequently, the corresponding transmission coefficient does not take into account the effects of the contact resistance associated to the switches in the down state. In order to overcome this shortcoming, a co-simulation procedure combining full-wave simulation in schematic circuit simulation has been adopted by adding, where necessary, the contribution of the contact resistance. More specifically, the contact resistance has been assumed equal to $1\,\Omega$ for series cantilever switch, while it has been assumed equal to $2\,\Omega$ for the shunt air-bridge switch.

The amplitude of the transmission coefficients calculated in this way are given in Figs. 9(a)–9(c), the corresponding insertion loss is illustrated in Fig. 9(d): values smaller than 1 dB have been obtained.

## 6. CONCLUSION

A composite right/left-handed (CRLH) transmission line (TL) with a reconfigurable phase shift and a constant equivalent characteristic impedance has been proposed. The unit cell of the line has been designed by using metal-insulator-metal capacitors and short-circuited stubs combined with MEMS switches to achieve reconfigurability. This way, a very compact and monolithic M-state CRLH TL well-suited for phase shifter applications has been obtained.

The proposed design strategy has been illustrated by fixing $M = 3$ and the working frequency equal to 1.8 GHz. Reported results demonstrate that, with respect to conventional printed transmission lines, the use of the CRLH TL approach leads to a consistent bandwidth broadening effect: by assuming $a \pm 5°$ phase error a relative bandwidth greater than 7% has been obtained in all states, whilst that calculated for a conventional microstrip line is about 3%. As for the use of MEMS technology, results demonstrate that values of the insertion loss smaller than 1 dB can be achieved. Finally, the proposed device occupies an area of only a few square millimeters.

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