Tunable Via-free Microstrip Composite Right/Left-Handed Transmission Lines Using MEMS Technology

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Abstract. In this contribution a tunable via-free microstrip composite right/left-handed transmission line (CRLH-TL) is designed and simulated. To add tunability RF MEMS elements are implemented in the interdigital capacitors and stub inductors, which match the line impedance during tuning. The via-free design enables easy and low-cost fabrication. Additionally, tunable zero-order resonators (ZORs) using two and three-cell CRLH-TL units, which have the resonant frequency tuning capability, are designed and simulated to verify the size-independent characteristic of ZORs.

1. Introduction

Metamaterials are of interest in order to realize novel components. They are artificial structures with electromagnetic properties not commonly found in nature. Typical realizations are three-dimensional structured materials containing cells with split-ring resonators (SRRs) or composite right/left-handed transmission lines (CRLH-TLs) [1]. But for those SRRs are based on the resonant phenomenon, their inherent drawbacks such as narrow bandwidth, high loss and fabrication difficulties limit the application to the microwave engineering. CRLH –TLs are a more practical approach, which are made up with additional series capacitance (C_L) and shunt inductance (L_L) other than unavoidable parasitic series inductance (L_R) and shunt capacitance (C_R) of the line as depicted in Figure 1. CRLH-TLs exhibit left-handed (LH) and right-handed (RH) behavior in the lower and upper frequency range. Since CRLH-TLs have unique characteristics such as negative phase constant, backward propagation and non-linear phase, many studies have been done to apply CRLH-TLs in various microwave engineering areas such as antennas, resonators and filters, etc.

Of increasing interest is the possibility to make those CRLH components tunable in order to provide various functionalities in one component. Many researchers have developed tunable CRLH-TLs to enhance their performance and widen its application areas by adding tunability. Those researches are mainly focused on changing the parameters of reactive loads, which have been realized with varactor diodes, pin-diodes or ferroelectric/superconductive materials. However those approaches suffer from high loss, poor yield, narrow tuning range, low operating frequency and low temperature condition for superconducting. Recently, Micro-Electro-Mechanical Systems (MEMS) are referred to be the best candidate which meet the challenging factors with low loss, high frequency operation, high linearity and virtually no power consumption, etc. Other features to be considered in the tuning of CRLH-TLs are impedance matching and balancing. In general, CRLH-TLs can only be matched in a restricted frequency band. However, as the formulae in Figure 1, when a purely right hand impedance (Z_R) and a purely left hand impedance (Z_L) are equal to the line impedance (Z_0), the CRLH-TLs are matched over an infinite bandwidth, which also allows balanced conditions where the shunt resonant frequency (ω_{sh}) is identical to the series one (ω_{se}). If only one load is tuned, the CRLH-TL, which is initially impedance matched and balanced, is no more matched and balanced, so at least two loading parameters should be tuned at the same time [2, 3].

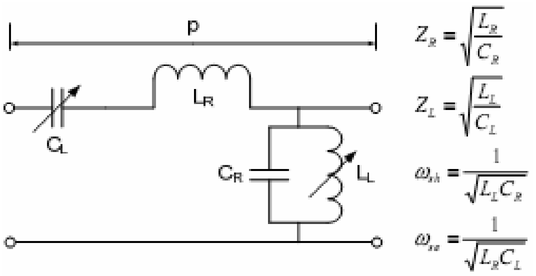


Fig. 1. Equivalent circuit of tunable CRLH unit cell with physical length p.

In this work, we propose a tunable CRLH-TL based on a microstip and monolithically integrated on a MEMS process. As conventional designs, the CRLH cell is designed by inserting tunable series capacitance (C_L) and shunt inductance (L_L) as in Figure 1. The cell simultaneously tunes C_L and L_L to account for the impedance change by reactive component change whereas many conventional ways are through tuning of only one component. Comparatively, a better matching is achieved. This is also advantageous to realize balanced CRLH-TLs, which is required to the specific application like broadband side radiating leaky wave antennas. The proposed structure is designed by a single planar metal layer and is via-free, which introduces low parasitic and loss besides simple fabrication process. By introducing radial stubs for grounding, we avoid the complex via penetrating process which deters cost effective fabrication. As another approach, the coplanar waveguide configuration, where the grounding is much easier for the ground conductors are same plane as signal's, can be considered, but it is not suitable for some applications like 2D texture surfaces [4, 5]. The MEMS elements in this study are based on the design by EADS Germany as reported in [6]. Compared to the conventional ones, they introduce low parasitic for their fabrication process and geometries are simple, which are advantageous to control and design.

2. Design and Simulation of Unit CRLH Cell

A. Tunable interdigital capacitor

In terms of the capacitance control, the Metal-Insulator-Metal (MIM) approach is more advantageous of realizing high capacitance due to the confined and dense electric field between metal electrodes. However, to avoid the fabrication complexity, we adopt planar interdigital capacitors (IC), which are easy to implement, as opposed to the MIM approaches which require complicated process. Figure 2 describes a tunable interdigital capacitor with two MEMS cantilever beams (IC1, IC2) for capacitance tuning. When the beam is down, the finger is more coupled with its neighboring finger, which leads to an increase of the capacitance. Likewise, the up-positioned beam decreases the capacitance. Consequently, an IC has maximum capacitance when all beams are down and minimum when they are in up-position. Unlike a normal switching operation, the beams in the IC have no contact parts, so are free of the contact problems. To achieve good impedance matching and balancing, the dimensions of IC are carefully determined by lumped element parameter extraction.

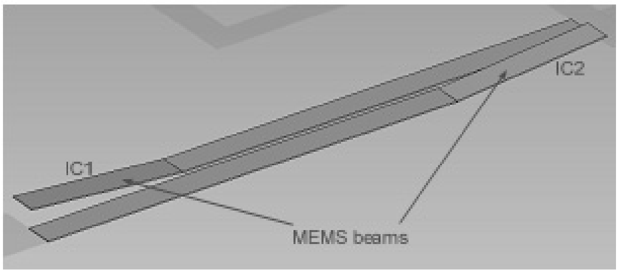


Fig. 2. Tunable interdigital capacitor.

B. Tunable stub inductor using radial stub

The tunable stub inductor is shown in Figure 3. Short circuited stubs which have three meander lengths make three different shunt inductances according to the state of six switches (RS1, RS2 and RS3). The switches are controlled by three signals. When a certain stub is connected to the main line, only two switches in one line are down whereas the other four switches are up. For stub grounding, a radial stub is introduced to avoid via-hole fabrication and achieve broadband operation, which also enables easy and cost effective fabrication.

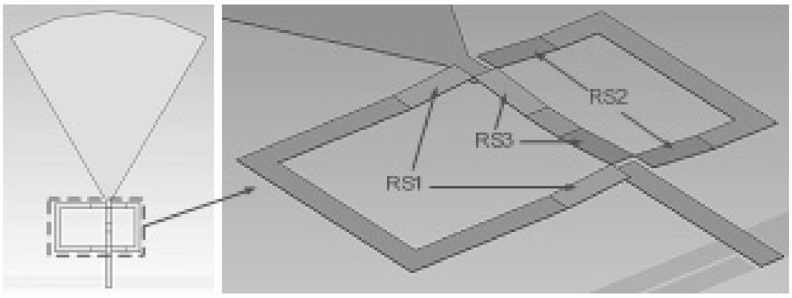


Fig. 3. Tunable stub inductor using radial stub.

C. Tunable CRLH cell

Figure 4 and Table 1 show the assembled CRLH unit cell and beam/switch state assignments to control it into three states while maintaining impedance matched and balanced conditions. In Figure 5(a), S_{21} parameters of CRLH lines with three CRLH-TL states are depicted through the simulation by CST Microwave Studio [7]. In the figure, we can see the frequency at which the phase of S_{21} is zero is changed for each state by 7.3, 8.2 and 9.6 GHz. Those frequencies are transition points between LH and RH regions on each state. The propagation constant (β) of one CRLH cell can be easily calculated from its ABCD parameter. For a reciprocal network which has the physical length p the following equation (1) is valid [8].

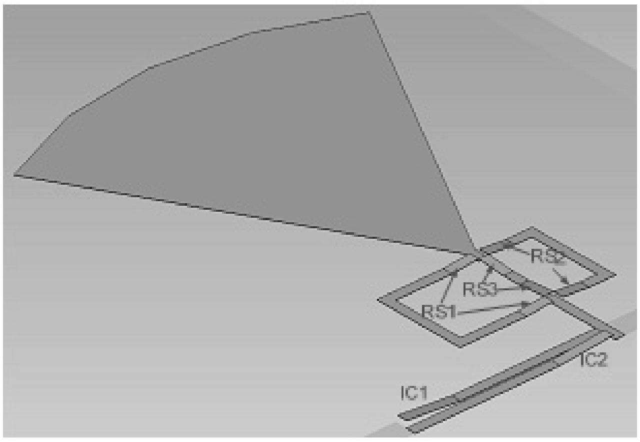


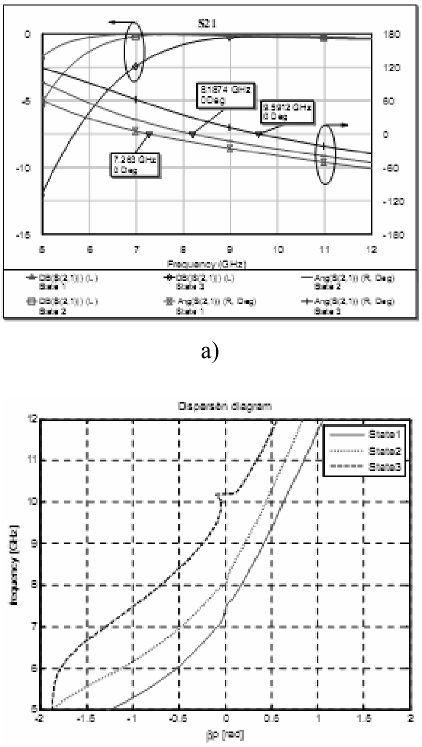
Fig. 4. Assembled CRLH unit cell.

Table 1. Beam/switch state assignments

	IC1	IC2	RS1	RS2	RS3
State 1	Down	Down	On	Off	Off
State 2	Up	Down	Off	On	Off
State 3	Up	Up	Off	Off	On

$$\alpha + j\beta = \frac{1}{p}\cosh^{-1}\frac{A+D}{2} \tag{1}$$

Generally, the right side term of (1) is a complex value and its imaginary part corresponds to the propagation constant β. Figure 5(b) shows calculated dispersion curves for each state. The figure depicts dispersion curve changes by reactive load tuning. At about 8 GHz, the wave propagates forward in state 1 (β>0). But in state 3 the propagation occurs in reverse direction (β<0) and even remains in the same position in state 2 (β=0). If our design frequency is 8 GHz, we can switch one state to another by changing beam/switch states. At other frequencies, we can still tune the propagation behavior just by the MEMS element state change without circuit modifications.



a)

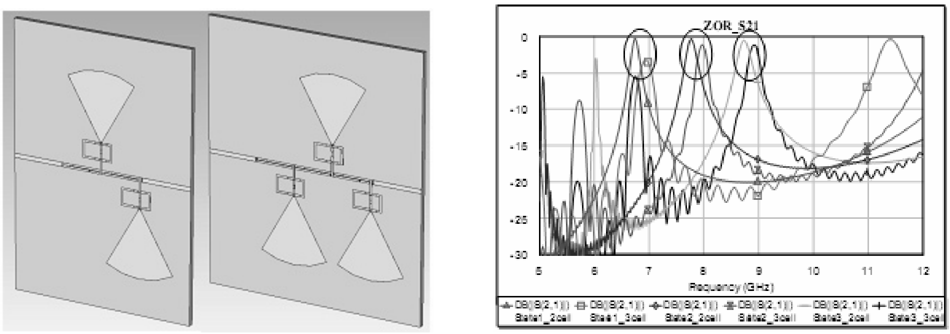
Fig. 5. (a) Magnitude and phase of S_{21} according to the state (b) Dispersion diagram.

Initially, all the states are designed to be always balanced regardless of tuning. However, state 1 and 2 are slightly unbalanced and clearly on state 3. This is mainly due to the loading parameter changes by element couplings, which is not considered in the parameter extraction before assembly. Moreover, compared to the reported CRLH design (mainly based on the Rogers material), the structure is much smaller and denser where a small coupling makes considerable changes to the loading parameters.

3. Zero Order Resonators

Open ended transmission lines produce standing waves due to the boundary condition and become resonators. The CRLH-TL resonators have unusual characteristics which allow negative and zero order resonant mode besides positive order operation as in normal transmission lines. The most interesting mode is zero order (β=0) where the CRLH-TL resonates at the infinite wavelength regardless of the transmission line length. In unbalanced case, it is shown that the resonant frequency of open ended resonators is determined by shunt components, which is different from the balanced frequency [1].

In Figure 6(a) open circuited CRLH-TL based ZORs of two- and three-cell configurations are shown. The cells are cross positioned to avoid radial stub overlap between cascading cells. On the same position of each cell, the switches are simultaneously controlled to get same loads. In Figure 6(b) it is observed that the resonating frequencies for each state are approximately the same regardless of the cell number, which verifies the zero order resonance.



a) b)

Fig. 6. (a) ZORs with 2, 3 CRLH unit cells (b) S21 on each state.

4. Conclusion

Tunable via-free, single-layered microstrip CRLH-TLs using RF MEMS technology are designed and simulated. MEMS beams and switches are used for changing reactive loads, which simultaneously tunes series conductance and shunt inductance for impedance matching and CRLH balancing. According to the beam/switch states, the propagation mode of CRLH-TL is changed, which is investigated by β-ω dispersion curves. The exact matching and balancing are still a significant developing task. Two designs of ZOR are simulated and discussed to confirm the infinite wavelength resonant characteristic. The resonant frequencies are not a function of line length but of the loading elements which are controlled by MEMS elements.

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