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Research Article

CRLH Transmission Lines for Telecommunications: Fast and Effective Modeling

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A different parameter extraction approach based on zero immittances for composite right/left-handed (CRLH) structure is presented. For lossless unit cell equivalent circuit model, LC parameters of series and parallel branches are extracted according to series resonance frequency and parallel resonance frequency, respectively. This approach can be applied to symmetric and unbalanced CRLH structures. The parameter extraction procedure is provided and validated by T-type unit cell model. The responses of distributed prototype and extracted equivalent LC circuit model are in good agreement. The equivalent circuit modeling can improve the degree of freedom in the CRLH TLs design. This parameter extraction method provides an effective and straightforward way in CRLH metamaterials design and applications in telecommunication systems.

1. Introduction

In telecommunication system, the role of the oscillator is to establish stable harmonic oscillation at a specific carrier frequency for modulation and mixing, which is shown in Figure 1(a). In the oscillator circuit, the main function of resonator is frequency selection and storage of energy. Conventional transmission line resonator is size dependent on frequency, which is not suitable for use in miniaturized integrated circuits. Composite right/left-handed transmission line (CRLH TL), introduced by Caloz and Itoh, is the transmission line (TL) approach of left-handed materials (LHMs) [1]. CRLH metamaterials with right-handed (RH) and left-handed (LH) properties have the advantages of low loss and wide bandwidth, which have been extensively studied and broad applied in guided-wave and radiated-wave devices for over decades [2–5]. Typically, the distributed CRLH TL is consisting of the series interdigital capacitor (IDC) and the shunt shorted stub inductor (SSI), which can be realized by the microstrip line and coplanar waveguide [4]. Based on CRLH TL structures zeroth-order resonator can be achieved; its size is frequency independent and can be realized, theoretically, arbitrarily small [6]. The schematic diagram of oscillator circuit using a zeroth-order resonator is shown in Figure 1(b). Using the zeroth-order resonator can effectively reduce the size of the oscillator circuit and improve the miniaturization of communication systems.

To accurately design CRLH TL and investigate the characteristics of CRLH TL-based devices, the equivalent circuit model is used to parameterize the complicated behaviors of the practical distributed circuits [7, 8]. The characteristics of the CRLH TLs are closely related to the LC parameters. Accurate design depends on whether the parameters meet the requirements. The design can be modified by parameter extraction in order to achieve optimum performances. In [9], to calculate the extracted LC parameters, the equivalent T and Π networks of IDC and SSI are separately characterized by admittance and impedance matrices; however coupling effects between IDC and SSI are not taken into account in this parameter extraction procedure. Otto et al. proposed an energy based method to extract equivalent circuit parameters [10], which was further implemented in [11]. However, this method requires the use of software for electromagnetic energy calculation, cannot be extracted by experiment. Based on effective medium concept, revised Nicolson-Ross-Weir (NRW) approach was applied to extract equivalent parameters. In this method, the equivalent circuit model parameters are deduced by the effective permittivity ε_r and the effective

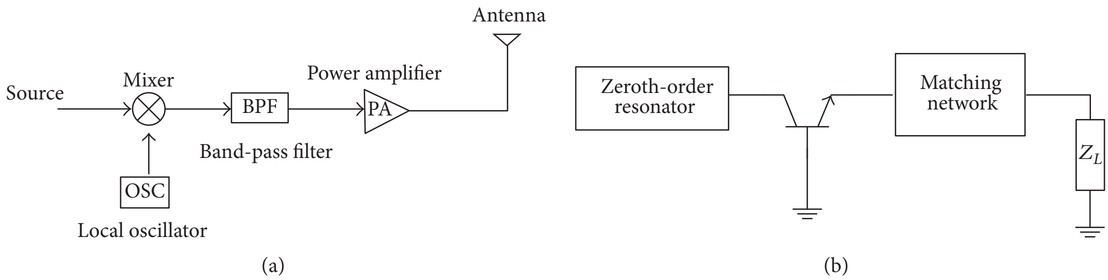

Figure 1: (a) The block diagram of telecommunication system. (b) The block diagram of oscillator.

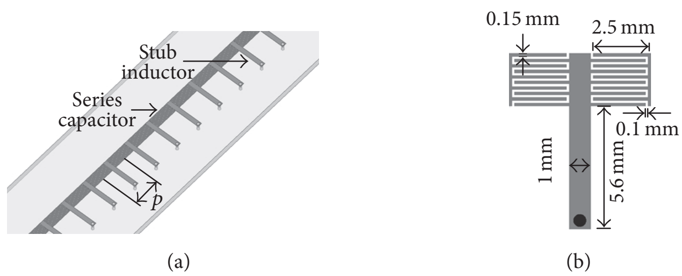

Figure 2: CRLH TL structures. (a) Periodic CRLH TLs with series capacitors and shunt stub inductors. (b) Geometry of unit cell of CRLH TL.

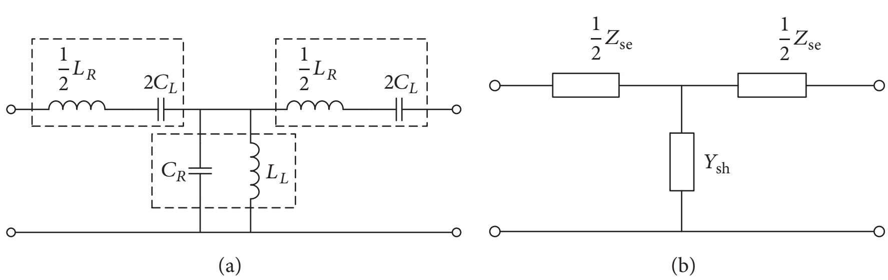

Figure 3: Equivalent circuit models of CRLH TL for parameters extraction. (a) T-type unit cell circuit model. (b) Equivalent network.

permeability μ_r. However, this method suffers multisolutions problem [12–15]. The equivalent circuit extraction method proposed in [16] employs the transmission-line-reflect (TLR) calibration to deembed the effects of the transmission lines. In this method both full-wave simulation and measured S-parameters are used to obtain the $ABCD$ transmission matrix of the CRLH unit cell.

In this paper, a different parameter extraction approach based on zero immittances has been presented. For lossless equivalent LC circuit model adopted, series resonance frequency and parallel resonance frequency are obtained from immittances characteristic, which is utilized to extract the LC parameters. In the proposed method, test transmission lines are placed in both sides of the CRLH structure. The effects of the transmission lines are eliminated by matrix calculation. The scattering parameter used can be obtained by full-wave simulations. The extraction procedure is convenient and effective and can be applied in unbalanced CRLH structures. This approach is illustrated by T-type unit cell model. The transmission characteristics of the distributed CRLH structure and the extraction LC equivalent circuit are in comparison with each other, and in wider bandwidth the extracted equivalent LC circuit model is effective.

2. Equivalent Circuit Modeling and Parameter Extraction Approach

The CRLH TL considered in this paper is constituted by series interdigital capacitor and parallel shorted stub inductors, which is shown in Figure 2(a). The dimensions are the same as those in [1], which is depicted in Figure 2(b). Assuming the transmission line is lossless, interdigital capacitor is modeled with C_L series L_R and stub inductor is modeled with L_C shunt C_R. The T-type unit cell circuit model of CRLH TLs is shown in Figure 3(a) and the corresponding microwave network is displayed in Figure 3(b).

Due to the unit cell circuit model shown in Figure 3, the immittances Z_{se} and Y_{sh} characteristics are plotted in

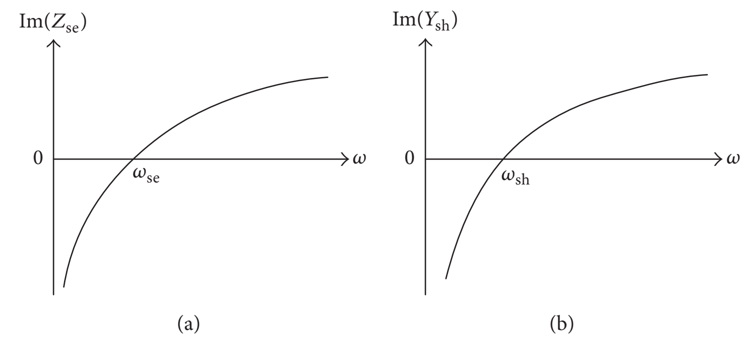

FIGURE 4: Immittances characteristics of T-type equivalent circuit model. (a) Series impedance Z_{se} characteristic curve. (b) Shunt admittance Y_{sh} characteristic curve.

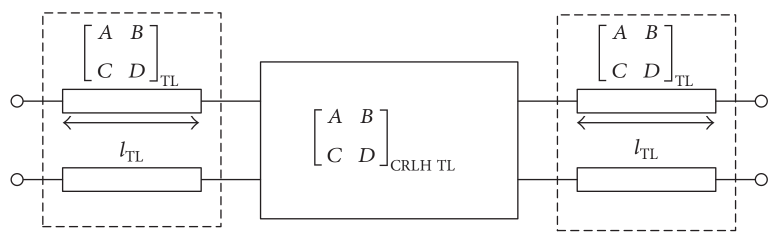

FIGURE 5: Parameter extraction circuit system model.

Figure 4. When we have zero immittances, the series resonance frequency ω_{se} and parallel resonance frequency ω_{sh} are obtained.

$$\omega_{se} = \omega|_{\mathrm{Im}(Z_{se})=0} = \frac{1}{\sqrt{L_R C_L}},$$
$$\omega_{sh} = \omega|_{\mathrm{Im}(Y_{sh})=0} = \frac{1}{\sqrt{L_C C_R}}. \tag{1}$$

Based on the characteristics of immittances Z_{se} and Y_{sh}, we introduce an extraction approach to yield simple expressions for C_L, L_R, L_C, and C_R. For a two-port network, depicted in Figure 2(b), Z_{se} and Y_{sh} can be described in terms of *ABCD* transmission matrix. Using standard network conversion formulas, the series impedance and parallel admittance can be written in terms of the *ABCD* parameters, which lead to

$$Z_{se}^{sym} = \frac{2(A-1)}{C},$$
$$Y_{sh}^{sym} = C. \tag{2}$$

With zero immittances Z_{se} and Y_{sh}, the series resonance frequency and the parallel resonance frequency are determined by

$$\mathrm{Im}(Z_{se})|_{\omega_{se}} = 0,$$
$$\mathrm{Im}(Y_{sh})|_{\omega_{sh}} = 0. \tag{3}$$

With ω_{se} and ω_{sh}, the LC parameters of series and parallel tank would be solved separately. And the corresponding extract parameters are determined by

$$L_R = \frac{1}{2}\frac{\partial}{\partial\omega}\,\mathrm{Im}(Z_{se})|_{\omega_{se}},$$
$$C_L = \frac{1}{\omega_{se}^2 L_{se}},$$
$$C_R = \frac{1}{2}\frac{\partial}{\partial\omega}\,\mathrm{Im}(Y_{sh})|_{\omega_{sh}},$$
$$L_L = \frac{1}{\omega_{sh}^2 L_{sh}}. \tag{4}$$

When $\omega_{se} = \omega_{sh}$, called balanced case, CRLH TLs would exhibit special properties. In practice, most initial fabrics are unbalanced, and with this extraction approach we can conveniently revise the design. That is, this extraction procedure is applicable for both balanced and unbalanced cases.

3. Extraction Procedure and Validation

This section provides the extraction procedure based on circuit model shown in Figure 3 and verifies this method with CRLH TLs proposed by Caloz and Itoh. Usually, in order to obtain the transmission matrix of CRLH TL, a section of microstrip transmission line (TL) has to be added at each end of the component in full-wave simulation; the diagram is shown in Figure 5. However, the added microstrip TLs would change the original network characteristics such as

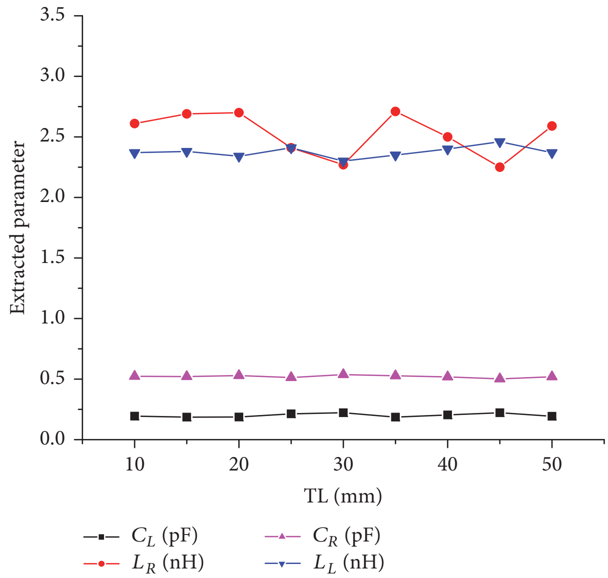

Figure 6: Extracted LC parameters of equivalent LC circuit model.

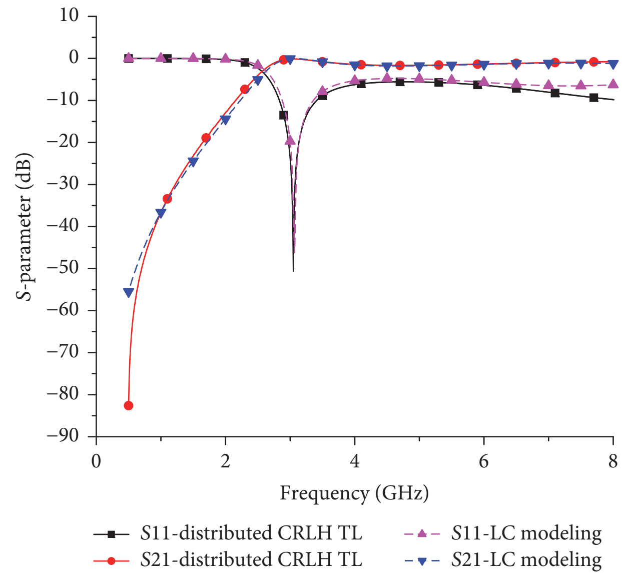

Figure 7: Comparison of S-parameters between distributed 1-cell CRLH TL and equivalent LC circuit model.

propagation phase. Therefore it is essential to eliminate the effect due to the test TLs.

The distributed CRLH TL and extracted equivalent circuit model are validated by comparing the scattering characteristics. The procedure is provided as follows:

(1) Do full-wave simulation for the distributed circuit of Figure 5 and test microstrip TL to get the S-parameters of overall circuit and TLs, respectively.

(2) Compute $[ABCD]$ of overall circuit and $[ABCD]$ of TL corresponding to the S-parameters obtained in (1) using standard network conversion formulas.

(3) Compute $[ABCD]$ of CRLH TL using

$$[ABCD]_{\text{overall}} = [ABCD]_{\text{TL}} [ABCD]_{\text{CRLH TL}} [ABCD]_{\text{TL}}. \quad (5)$$

(4) Compute the Z_{se} and Y_{sh} vector using again standard network conversion formulas.

(5) Find zero points of Z_{se} and Y_{sh} using interpolation method to determine series resonance frequency ω_{se} and parallel resonance frequency ω_{sh}.

(6) Compute the C_L, L_R, L_C, and C_R using (4).

(7) With extraction parameters obtained from (6), simulate the equivalent LC circuit model and compare with distributed CRLH TL.

The CRLH TLs proposed by Caloz and Itoh and shown in Figure 1 is considered here to illustrate the parameter extraction procedure with T-type unit cell circuit model. Full-wave simulation and numerical calculation are developed; the extraction results are presented in Figure 6. With different test TL lengths, the extracted LC parameters are mainly stable. It should be noted that, since the test transmission lines are series with the interdigital capacitor, the different transmission line length has a great influence on the L_R parameter. In the process of parameter extraction, the L_R value can be obtained by multiple extractions and averaging.

The set parameters $L_R = 2.56$ nH, $C_L = 0.192$ pF, $C_R = 0.523$ pF, and $L_L = 2.33$ nH of T-type unit cell circuit with TL = 20 mm has been selected for comparison with practical distributed structure. In Figure 7, S-parameters of distributed 1-cell CRLH TL structure and equivalent LC circuit model are presented. As shown in comparison results, within wider bandwidth, they are in good agreement with each other.

The CRLH TL is balanced when the series and shunt resonant frequencies are equal; on the contrary, the CRLH TL is unbalanced when the series and shunt resonant frequencies are different. It is noted that the series and parallel LCs are extracted from ω_{se} and ω_{sh}, respectively. Regardless of whether the series resonant frequency and the parallel resonant frequency are equal, this extraction method can model the CRLH TLs. This makes it convenient to apply this approach in both balanced and unbalanced CRLH structures.

4. Conclusion

A zero immittances based parameter extraction approach for distributed CRLH structures has been proposed, which is applicable to symmetric unit cells. According to series resonance frequency ω_{se} and parallel resonance frequency ω_{sh}, determined by immittances characteristics, LCs of series branch and parallel branch are extracted, respectively, and therefore this method can be used in unbalanced CRLH structures. The presented extraction procedure provides an effective and straightforward way in CRLH metamaterials design and application of telecommunication system. Finally, the authors are currently applying this approach in analysis of CRLH metamaterials-based microwave circuit.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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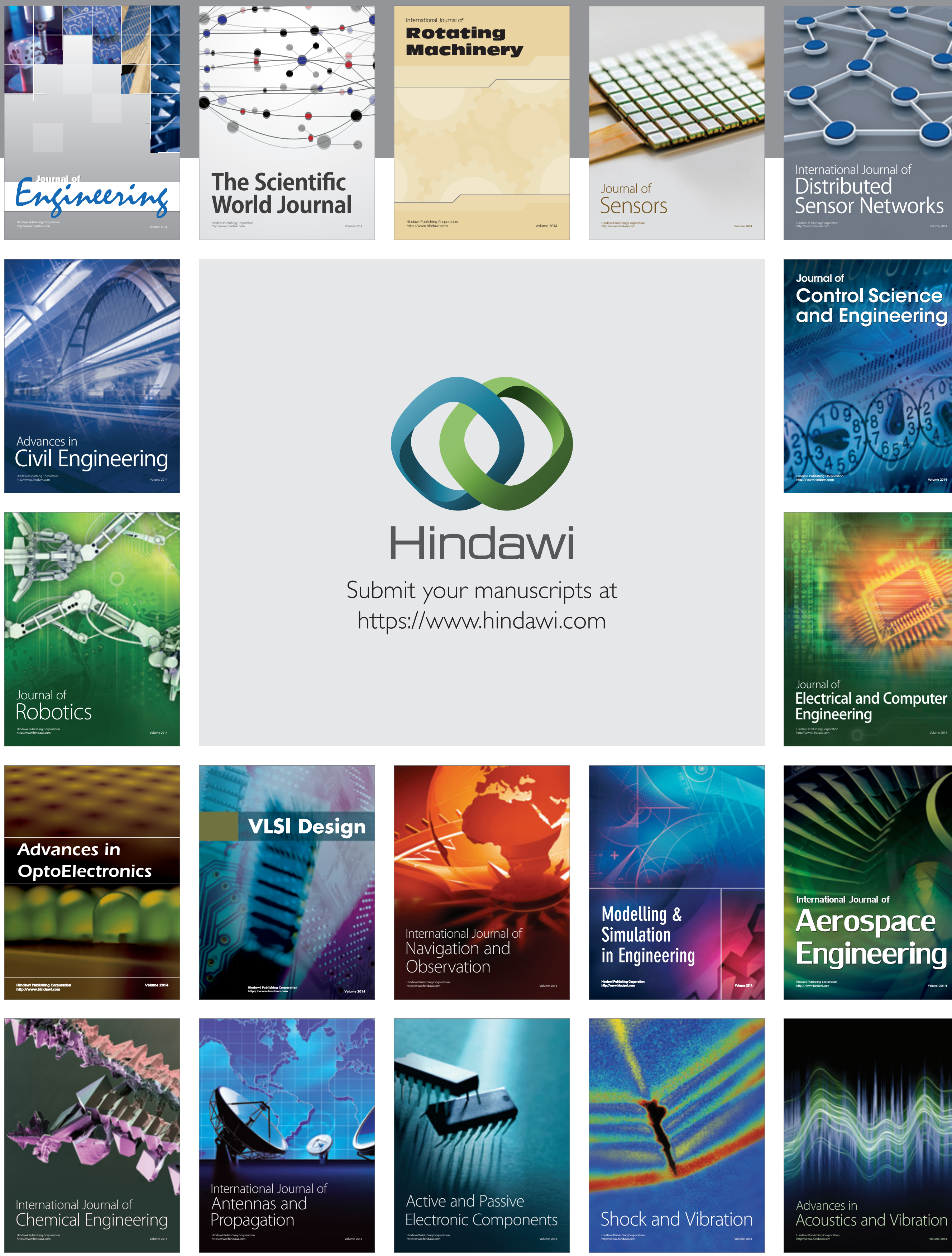
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