

## A NEW MICROSTRIP COMPOSITE RIGHT/LEFT-HANDED TRANSMISSION LINE IMPLEMENTATION

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*Se prezintă o nouă formă de implementare în tehnologie microstrip a unei linii artificiale de transmisiune CRLH. Celula unitară a noii linii artificiale este formată din următoarele elemente înseriate: o linie de transmisiune, un capacitor interdigital, o a doua linie de transmisiune și un tronson de linie în paralel terminat în scurtcircuit. Prin adăugarea celor două linii, rezonanțele parazite ale capacitorului sunt deplasate în afara benzii de lucru, iar frecvența de tranziție a celulei poate fi aleasă dintr-o gamă mai largă de frecvențe. Noua formă este comparată cu alte implementări microstrip. Caracteristicile noii linii artificiale sunt demonstrate atât prin simulări cât și prin rezultate experimentale.*

*A new microstrip implementation of a composite right/left-handed (CRLH) transmission line is presented. The unit cell of the new artificial line consists of a series of one transmission line, an interdigital capacitor, another transmission line and one short-terminated stub. When the transmission lines are introduced, the parasitic self-resonances of the capacitor are shifted outside the operational band and the transition frequency of the cell can be chosen from a broader range of frequencies. This solution is compared with other microstrip implementations of CRLH cells. The characteristics of the newly designed artificial transmission line are demonstrated by –full-wave simulations and measurement results.*

**Keywords:** metamaterials, composite right/left-handed (CRLH), artificial transmission line, interdigital capacitor

### 1. Introduction

Several composite structures that emulate mediums with simultaneously negative permittivity and permeability (left-handed materials which are not readily available in nature) have been presented in literature [1, 2]. The initial metamaterial structures [3] were of little practical interest for engineering applications because they have resonant behaviour, and consequently exhibited high losses and narrow bandwidth. Left-handed (LH) artificial transmission lines partially overcome this problem because they are not resonant type, so losses are smaller and the operating frequency band is wider [4]. This type of artificial line

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is a promising candidate for different microwave applications, such as: couplers [5], delay lines [6], resonators [7], leaky-wave antennas [8-10] and dual-band components [11]. A left-handed transmission line can be simulated by cascading cells constituted by two LH elements: a series capacitance  $C_L$  and a shunt inductance  $L_L$ . This configuration is the dual circuit of the conventional transmission line, which contains cells constituted by a series right-handed (RH) inductance  $L_R$  and a shunt RH capacitance  $C_R$ . However, a pure LH line cannot exist due to the inherent right-handed effects of the physical LH elements which lead to a combined behaviour, the so-called composite right/left-handed transmission line (CRLH TL) [12]. The equivalent circuits of an asymmetric and a  $\pi$ -symmetric CRLH unit cell with electrical length  $\Delta\phi$  are shown in Fig. 1. For a balanced cell, the series  $\omega_{se}$  and shunt  $\omega_{sh}$  resonances are equal to the transition frequency  $\omega_o$ , which can be written as [4]:

$$\omega_o = \frac{1}{\sqrt{L_R C_L}} = \frac{1}{\sqrt{L_L C_R}} \quad (1)$$

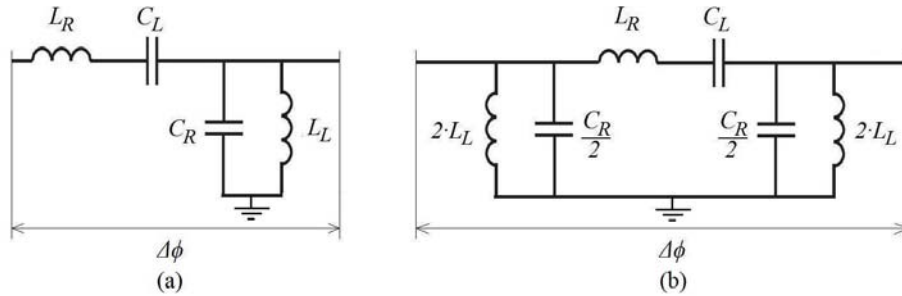


Fig. 1. Equivalent circuits for: (a) an asymmetric CRLH cell, (b) a  $\pi$ -symmetric CRLH cell

A cell with similar behaviour to that of these circuits can be built in microstrip technology using an interdigital capacitor (IDC) and a shunt short-terminated stub (which provide the LH capacitance and respectively the LH inductance). The series inductance and shunt capacitance are mainly given by the current and respectively voltage gradients across the interdigital capacitor [2]. The classical microstrip cell (Fig. 2a) proposed in [4] has one major drawback: the parasitic resonances caused by the multiconductor nature of the interdigital capacitor can occur within the desired operational band. An expensive solution to this problem is given in [13] by using bonding wires across the alternate fingers of the classical cell's capacitor (wire bonded classical cell, shown in Fig. 2b). Further, in [14] is presented a composite right/left-handed cell based only on wire bonded interdigital capacitors (WBIDC cell, shown in Fig. 3). This paper presents a modified microstrip CRLH cell implementation that eliminates the self-

resonances from the passband of the artificial line in a simpler manner. The new cell's characteristics are emphasised by comparing it with the classical cell and with the two types of wire bonded cells.

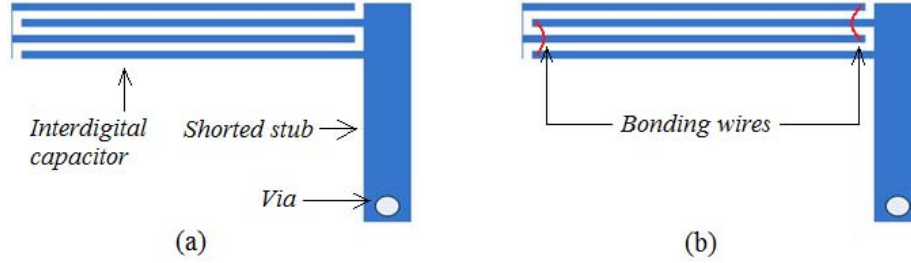


Fig. 2. (a) Classical CRLH cell, (b) Wire bonded classical CRLH cell.

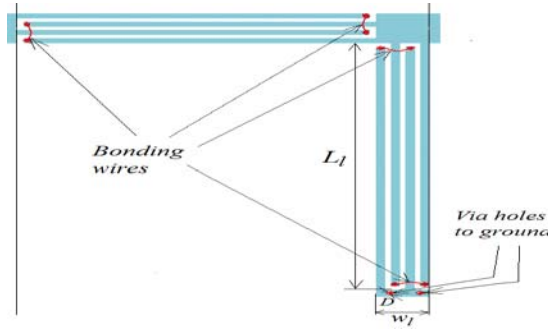


Fig. 3. Wire bonded interdigital capacitors cell (WBIDC cell).

## 2. Analysis of the modified microstrip CRLH cell

The modified unit cell shown in Fig. 4 is constituted by an interdigital capacitor ended with two transmission line sections and a stub shorted through a via to the ground (this cell is called from now on TLs cell because the difference from the classical cell consists in the additional transmission lines). The goal of the TLs cell is to diminish the effect of the parasitic resonances of the interdigital capacitor on the passband of the resulting artificial line. The self-resonance frequencies of the interdigital capacitor decrease as the capacitance increases (which means an increase in the capacitor's length if the number of fingers is constant) [13]. So, the first resonance frequency may enter the passband if the capacitor's length gets greater than a certain value. To avoid this problem, the length of the capacitor should be constrained to a maximum value which imposes higher limits for both the LH capacitance and the RH inductance ( $C_{LM}$  and  $L_{RM}$ , respectively):

$$\begin{aligned} C_L &< C_{LM} \\ L_R &< L_{RM} \end{aligned} \quad (2)$$

This leads, according to Equation (1), to a minimum attainable value for the transition frequency of a balanced cell. As a result, in some cases (for some design specifications), the cell may not be balanced at the desired frequency if the only way of controlling the series resonance is varying the capacitor's length (which is the case for the classical microstrip CRLH cell).

Taking into account the two transmission line sections of the proposed TLs cell, the RH elements can be increased without a further increase of the capacitor's length. In consequence, the series resonance frequency can be roughly written in terms of the transmission line sections length  $l_t$  and the inductance per unit-length  $L'$  as:

$$\omega_{se} = \frac{1}{\sqrt{(L_{RM} + 2 \cdot L' \cdot l_t) \cdot C_{LM}}} \quad (3)$$

Equation (3) shows that the series resonance can be lowered only by increasing the lengths of the two transmission line sections. Although the two transmission lines also increase the RH capacitance, the shunt resonance can be easily adjusted to match the series resonance by modifying the length of the stub. Thus, the transition frequency can be set to lower values than for the classical cell with the help of the additional transmission line sections. Additionally, if the TLs cell would be optimized for a leaky-wave antenna, an increase of the radiation range is also possible, as explained in [10].

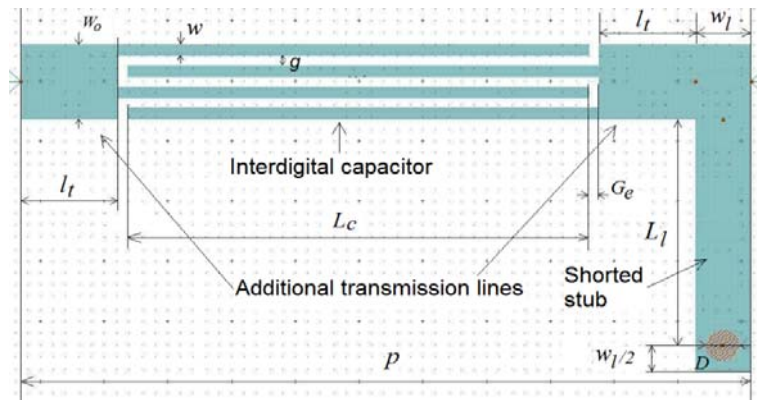


Fig. 4. Modified microstrip CRLH unit cell (TLs cell).

### 3. Unit cell simulations

The simulations were done using the method of moments from Agilent ADS. In order to compare the modified microstrip unit cell with other implementations (classical cell and wire bonded cells) all four cells were designed and optimized for a substrate with a relative dielectric constant  $\epsilon_r = 3$  and a thickness  $t = 0.508 \text{ mm}$  imposing the transition frequency at about 3.6 GHz. This goal translates in a cell with almost total transfer and zero phase-shift at the transition frequency. The classical cell was designed according to a procedure similar to the one given in [15]. The design procedures of the TLs cell and the wire bonded ones started from the main dimensions obtained for the classical cell. For the wire bonded classical cell, only minor size adjustments were necessary in order to counterbalance the effect of the wires on the transition frequency. In the case of the WBIDC cell, the parameter tuning process was done as described in [14]. For the TLs cell, the variables used in the optimization algorithm (an iterative gradient method and fine tuning) were: the capacitor's finger length  $L_c$ , the length of the stub  $L_l$  and the length of the two transmission line sections  $l_t$  (which has to be constrained to a maximum value in order to maintain the effective homogeneity condition:

$$\Delta\phi < \frac{\pi}{2} \Leftrightarrow p < \frac{\lambda_g}{4} \quad (4)$$

where  $p$  is the cell length and  $\lambda_g$  the guided wavelength [2]).

The main dimensions of the optimized cells are given in Table 1. The capacitors used for all four cells have some common parameters: four fingers, total width  $W_o = 1.27 \text{ mm}$ , finger width  $w = 0.22 \text{ mm}$ , gap between fingers  $g = 0.13 \text{ mm}$ , and the gap finger-line  $G_e = 0.15 \text{ mm}$ .

Table 1

**Main dimensions of the designed cells**

Parameter (mm) / Cell type	TLs cell	Classical cell	Wire bonded classical cell	WBIDC cell
$L_c$ (series capacitor finger length)	7.24	8.30	8.35	8.15
$l_t$ (length of the transmission lines)	1.52	-	-	-
$L_l$ (stub/shorted shunt capacitor length)	3.76	4.60	4.58	10.27
$w_l$ (stub/shorted shunt capacitor width)	0.87	0.87	0.87	1.27
$D$ (via diameter)	0.50	0.50	0.50	0.20
$p$ (unit cell length)	11.45	9.47	9.52	9.72

The scattering matrix elements and the group delay for the designed cells are shown in Figs. 5-6. Near the transition frequency (around 3.6 GHz), the

phase-shift is almost zero and the return loss gets below -30 dB, which shows that all cells are well balanced. The passband is divided in two regions: LH and RH, depending if the frequency is lower, respectively higher than the transition frequency. The -3dB passbands obtained from the insertion loss plots are summarized in Table 2. The wire bonded classical cell has the largest combined LH-RH passband (mainly provided by the RH side, which may not be always useful), followed by the TLs cell. The classical cell has a relatively large LH band, but the parasitic resonances make its RH band the narrowest from all four cells. In the case of the WBIDC cell, the resonances are shifted at higher frequencies than in the case of the TLs cell, but its LH region is very narrow.

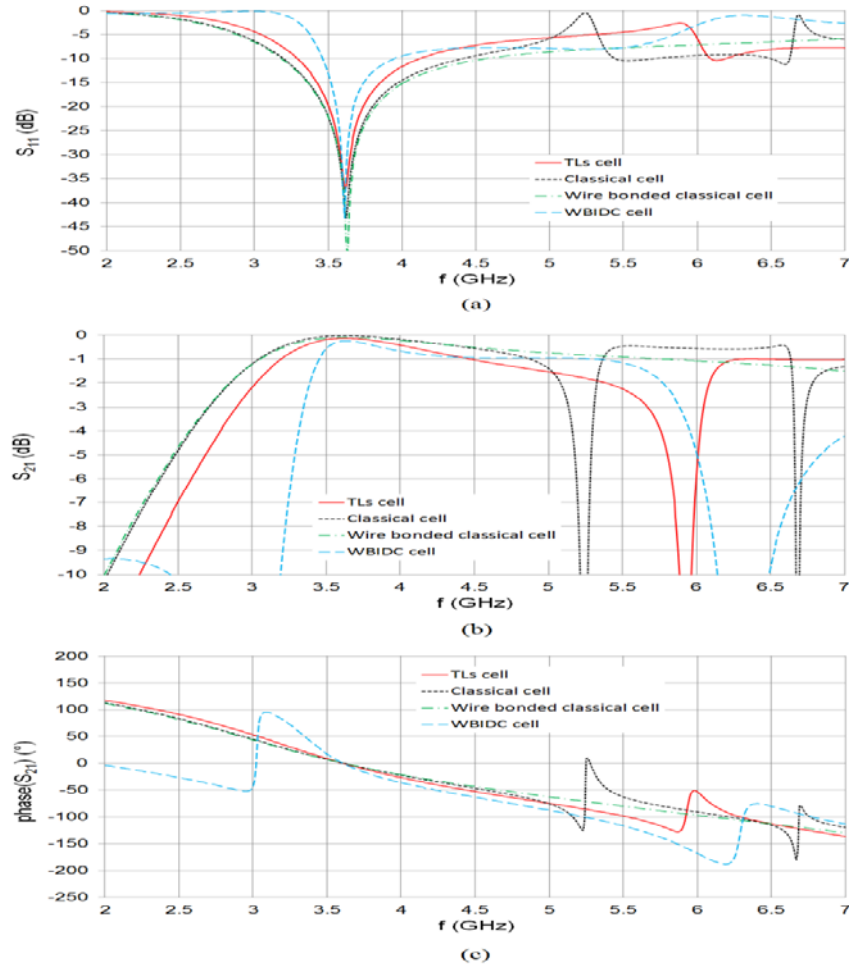


Fig. 5. Scattering matrix elements of the four unit cells : (a) return loss, (b) insertion loss, (c) phase-shift.

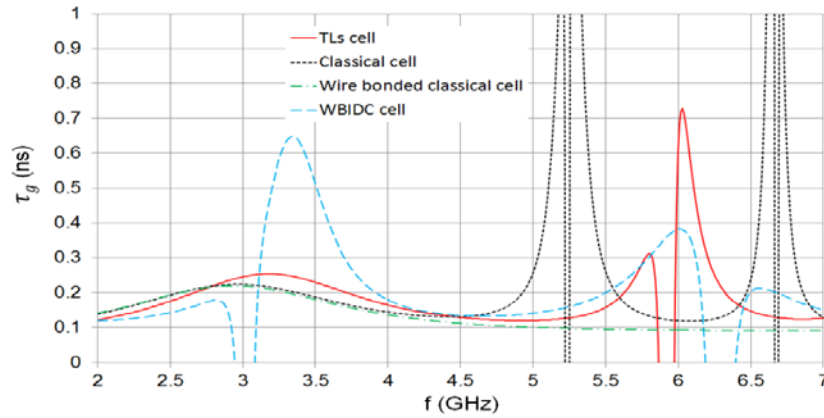


Fig. 6. The group delay of the four cells

Table 2

Passbands for the designed cells

Frequency (GHz) / Cell type	TLs cell	Classical cell	Wire bonded classical cell	WBIDC cell
Transition frequency	3.61			
LH region start frequency	2.89	2.70	2.70	3.35
RH region end frequency	5.67	5.14	> 7	5.88
Passband	2.78	2.44	> 4	2.53

The group delay of the WBIDC cell has a maximum value and steep slopes that can distort signals with large bandwidths. All other three cells have a relatively flat group delay. Concluding, the frequency-shift of the parasitic resonances provided by the TLs cell can't be as large as the one caused by the wire bonded alternatives, but the cell is simpler/cheaper and provides a relatively large combined LH-RH bandwidth.

#### 4. Experimental results

In order to verify the simulated characteristics of the TLs cell, a 10-cell artificial transmission line was built and measured. The physical dimensions of the prototype's cells are those presented in the previous section. Fig. 7 shows a picture of the prototype fabricated on a Rogers RO3003 substrate ( $\epsilon_r = 3$ ,  $t = 0.508$  mm,  $\tan(\delta) = 0.0013$ ). The width of the feed line was chosen 1.27 mm which yields the characteristic impedance  $Z_0 = 50 \Omega$ . To obtain minimal return loss, the dimensions of the ending stubs were fine-tuned ( $L_l' = 5$  mm,  $w_l' = 0.52$  mm) so that the unit cell becomes  $\pi$ -symmetric [8]. The return and insertion losses of the prototype are shown in Fig. 8. Fig. 9 shows the group delay in the passband of the 10-cell artificial line.

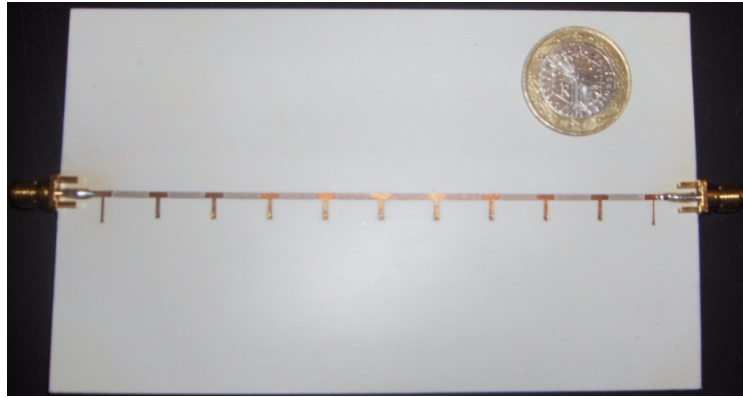


Fig. 7. 10-cell CRLH artificial transmission line prototype

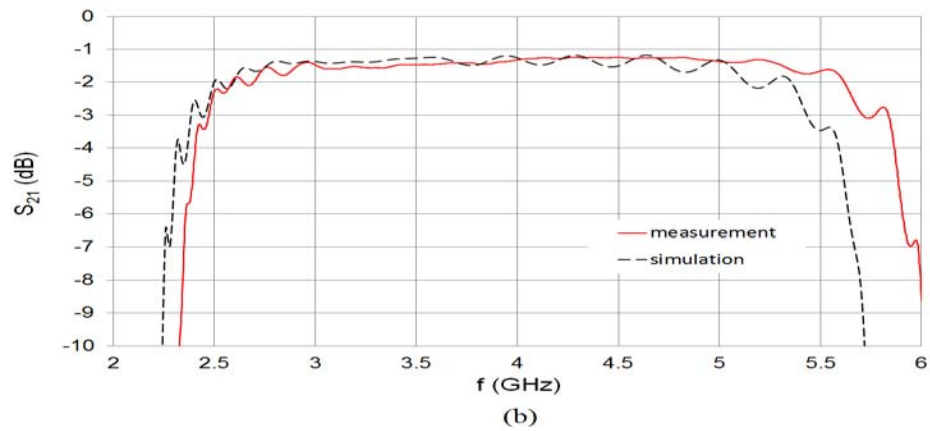
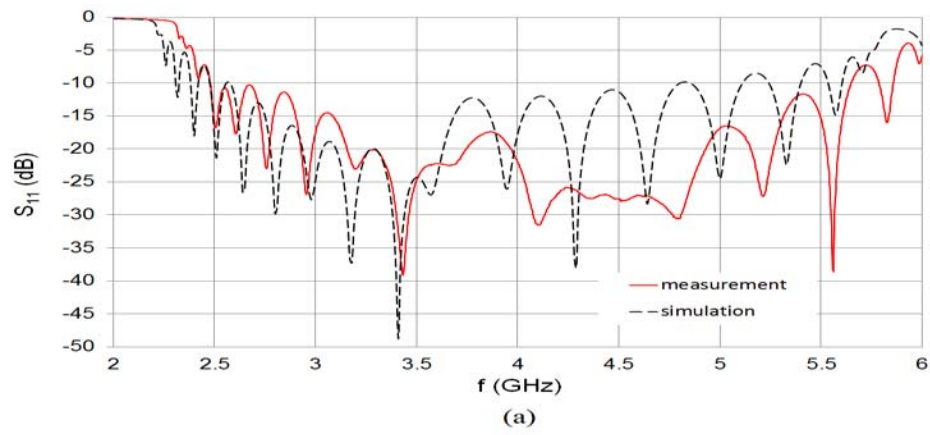


Fig. 8. 10-cell CRLH artificial line (a) Return loss, (b) Insertion loss



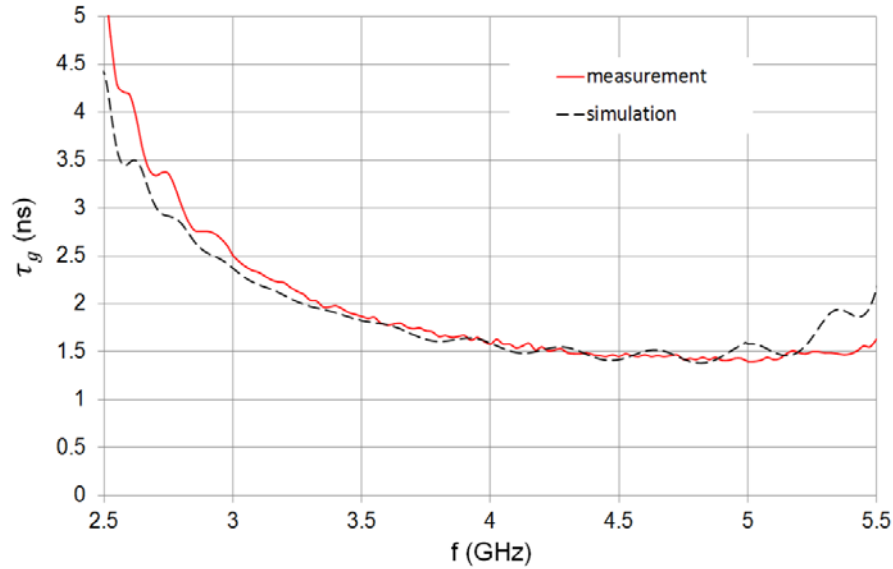


Fig. 9. Group delay of the 10-cell CRLH artificial line

The artificial transmission line behaves as a band-pass filter with a band similar to the one of the unit cell with practically no discontinuity at the transition frequency (which emphasizes that the line is very well balanced). The measured passband is slightly larger than the simulated result. The group delay of the artificial line decreases with frequency in the LH side of the passband and is relatively constant in the RH region. Overall, the measured response is seen to be in good agreement with the full-wave simulations in the operational band.

## 5. Conclusions

A new type of implementation of a composite right/left-handed transmission line as a planar structure in microstrip technology is presented. The new unit cell of the designed artificial line has in addition to the classical microstrip cell two transmission lines. Introducing the transmission lines, the parasitic self-resonances of the interdigital capacitor can be shifted to higher frequencies, and consequently the passband can be increased. Compared to other microstrip solutions to the parasitic resonances problem, this cell is more simple and cheaper to fabricate, although it may not extend the operational band in any situation as much as the alternatives that use bonding wires. A 10-cell prototype was built and measured and the experimental results shown very good agreement with the simulated ones.

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