A Distributed Mixer-Based Nonreciprocal CRLH Leaky Wave Antenna for Simultaneous Transmit and Receive

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2021 IEEE/MTT-S International Microwave Symposium - IMS 2021 | 978-1-6654-0307-8/21/$31.00 ©2021 IEEE | DOI: 10.1109/IMS19712.2021.9574840

***Abstract*—A nonreciprocal composite right/left-handed (CRLH) leaky wave antenna (LWA) based on a distributed mixer (DM) is proposed to achieve simultaneous transmit and receive (STAR). The DM structure consists of field-effect transistors (FETs) as mixing devices with a CRLH transmission line (TL) as the drain line and a microstrip line as the gate line. In the receive mode, the carrier LO signal in the gate line and the RF signal in the drain CRLH TL are along the same direction, while in the transmit mode, the RF signal is injected from the drain CRLH line at the opposite direction of the carrier LO signal from the gate line. Owing to distributed mixing principle, it will be shown that the reverse conversion gain for the down-converted IF signal can provide isolation between the transmit and receive operation, i.e. RF signals of opposite directions, thereby enabling the simultaneous transmit and receive characteristic.**

***Keywords*— Composite right/left-handed-transmission lines (CRLH TLs), distributed mixers (DMs), leaky wave antennas (LWAs), non-reciprocal, simultaneous transmit and receive.**

I. INTRODUCTION

Distributed mixers (DMs) have been traditionally used to achieve wideband mixing based on signal propagation along actively coupled artificial transmission lines (TLs) [1], [2]. Recently, CRLH TL-based distributed circuits exhibiting exotic material properties, such as negative phase velocity and propagation constant, are incorporated to expand the functionalities of the original DM concept, such as dual band mixing and wideband imaging rejection [3]–[5], as well as in distributed amplifiers [6]-[13]. On the other hand, time varying TLs demonstrating nonreciprocity have been proposed in [14], [15], in [14] the nonreciprocity is achieved by modulating the periodically loaded varactors along the TL in the time domain, forming a direction dependent mixing behavior subject to the propagation direction of an external carrier. Such characteristic is essentially analogous to the DM mechanism.

Based on this observation, this work proposes a new type of CRLH non-reciprocal leaky wave antenna based on distributed mixing principle that can be used for simultaneous transmit and receive, as illustrated in Fig. 1. The proposed nonreciprocal DM structure utilizes FETs as mixing elements along with a CRLH TL as the drain line and a microstrip line as the gate line. In the receive mode, the carrier LO signal in the gate line and the RF signal in the drain CRLH TL are along the same direction, while in the transmit mode, the RF signal is injected from the drain CRLH line at the opposite direction of the carrier LO signal from the gate line. It will be shown that by utilizing the distributed mixing principle, the reverse conversion gain for the down-converted IF signal can provide isolation between the transmit and receive operation of the RF signal, thereby enabling simultaneous transmit and receive.

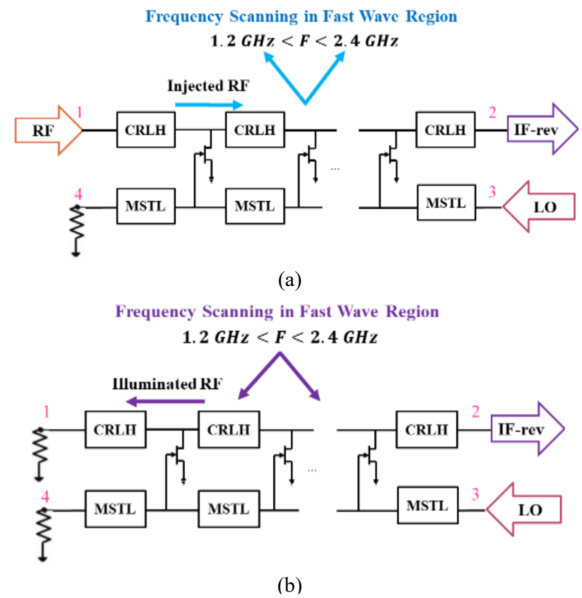

Fig. 1. Proposed simultaneous transmit and receive CRLH nonreciprocal leaky wave antenna: (a) transmit mode; (b) receive mode.

II. OPERATING PRINCIPLES

Typical distributed mixers use two conventional TLs connected to active components such as diodes or transistors to form nonlinear mixing [1]. Unlike the conventional DM scheme operating as gate mixers, where both RF and LO are injected from the gate side, in the proposed DM-based CRLH LWA shown in Fig 1, the RF signal is injected from the drain CRLH TL, whereas the LO is injected from the gate TL. The forward conversion gain (G_{fwd}) with respect to Port 1, and reverse conversion gain (G_{rev}) with respect to Port 2 can be calculated in terms of g_1 (conversion transconductance), $Z_{\pi d}$ (drain line impedance), β_g (gate line wave number), β_d (drain line wave number) and n (number of unit-cells) as follows:

$$G_{fwd} = \frac{P_{IF\_fwd}}{P_{RF}} = \frac{g_1^2}{16} Z_{\pi d}(f_{IF}) Z_{\pi d}(f_{RF}) \left| \frac{sin\frac{n\theta_f}{2}}{sin\frac{\theta_f}{2}} \right|^2 \quad (1)$$

$$G_{rev} = \frac{P_{IF\_rev}}{P_{RF}} = \frac{g_1^2}{16} Z_{\pi d}(f_{IF}) Z_{\pi d}(f_{RF}) \left| \frac{sin\frac{n\theta_r}{2}}{sin\frac{\theta_r}{2}} \right|^2 \quad (2)$$

where in the transmit mode:

$$\theta_f = |\beta_d(f_{RF}) + \beta_g(f_{LO})| - \beta_d(f_{IF}) \quad (3)$$

$$\theta_r = |\beta_d(f_{RF}) + \beta_g(f_{LO})| + \beta_d(f_{IF}) \quad (4)$$

and in the receive mode:

$$\theta_f = |\beta_d(f_{RF}) - \beta_g(f_{LO})| - \beta_d(f_{IF}) \quad (5)$$

$$\theta_r = |\beta_d(f_{RF}) - \beta_g(f_{LO})| + \beta_d(f_{IF}) \quad (6)$$

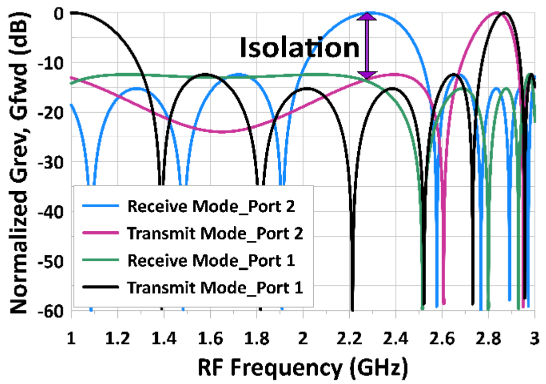

Fig. 2. Calculated Normalized G_{rev} when LO = 3.3 GHz

In both transmit and receive modes, IF at port 2 is termed IF-rev, indicating a reverse direction with respect to the LO injection at port 3. From (2) and (6), the maximum reverse conversion gain G_{rev} is obtained when $\theta_r = 0$ in the receive mode at Port 2, shown in Fig. 1(b). Assuming the IF signal is in the LH region, and the RF signal belongs to the right-handed (RH) region of CRLH TL, since $\beta_g(f_{LO})$ is non-negative for a conventional microstrip line (gate line), we can have maximum reverse conversion gain in the receive mode by choosing an appropriate IF to let (6) become zero. Moreover, in this case, $\theta_r \neq 0$ for the transmit mode as shown in (4), and therefore we can expect good isolation of the IF signal between the transmit and receive mode in the reverse port (Port 2). On the other hand, if the RF signal is in the left-handed (LH) region, according to (6), $\beta_d(f_{IF})$ should be more negative in order to have $\theta_r = 0$ in the receive mode, thereby resulting in a lower frequency for the IF signal at Port 2.

Fig. 2 plots the normalized reverse gains and forward gains based on (1) and (2), where the propagation constant β_d is calculated according to the dispersion diagram of an ideal CRLH with the unit cell parameters of $C_R = C_L = 2\,pF$, $L_R = L_L = 5.4\,nH$. It can be seen that G_{rev} has $sinc^2$ type behaviour and when LO = 3.3 GHz and RF = 2.28 GHz (IF = 1.02 GHz), the IF power reaches to its maximum at Port 2, where the isolation can be clearly seen between the transmit and receive mode at Port 2. As such, by using the CRLH TL on the drain side as a LWA, nonreciprocity can be achieved to realize simultaneous transmit and receive through the IF signal.

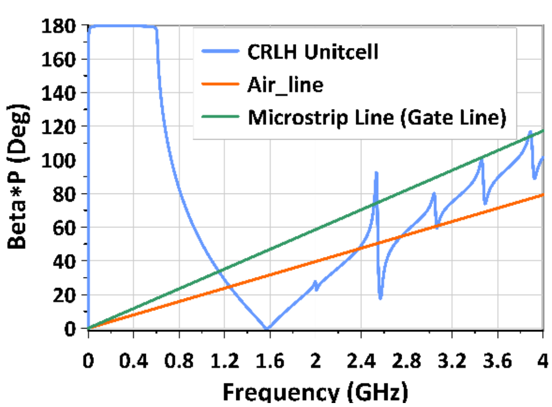

Fig. 3. Dispersion Diagram of CRLH Unit cell (drain), microstrip line (gate) and air line

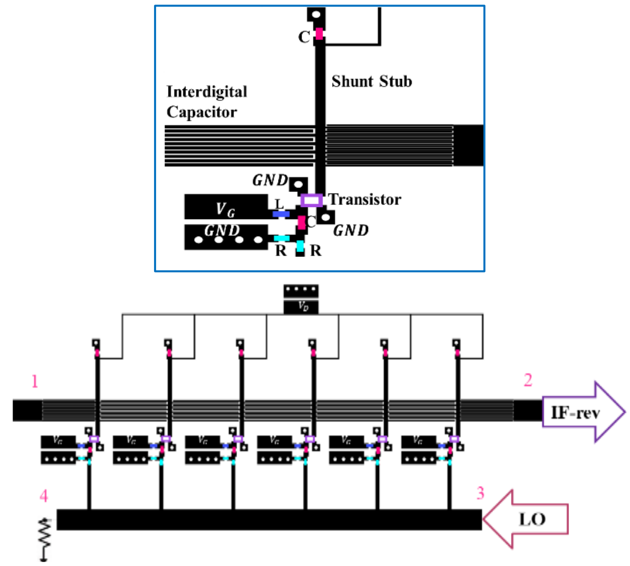

Fig. 4. Schematic of the proposed structure

III. Design

A. Unit cell Design

CRLH unit cells with interdigital capacitors and shunt stub inductors are used to realize the CRLH LWA on the drain side [16]. The dispersion diagram is shown in Fig. 3, where the center frequency of unit cell is designed to be 1.55 GHz. The fast wave region, determined by the intersection between the air line and dispersion diagram of CRLH unit cell, is from 1.3 to 2.3 GHz. A small band gap around center frequency is expected after loading the active part due to the drain-source capacitance of FETs (C_{ds}). The RF signal injected from drain side will operate in the fast wave region, whereas the down-converted IF signal is in the guided wave region. The dispersion curve for the gate microstrip line where the LO signal is injected (Port 3) is also shown in Fig. 3 for comparison.

B. A 6-Cell CRLH DM Prototype

As shown in Fig. 4, a six unit cell-CRLH DM is used for simulation and evaluation of isolation performance with respect to the down converted signal (IF) in Port 2. The prototype circuit is fabricated on a RT/duroid 5870 substrate (ε_r =2.33,

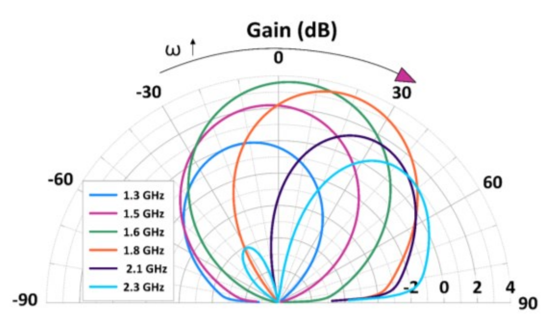

Fig. 5. Gain of 6 cells CRLH leaky wave antenna before loading active part in Phi=0 cut

$h = 1.57mm$). In addition, NE3509M04 transistor is used for the mixing elements, where the transistor drain is biased from the end of each shunt stub of CRLH unit cell connected to a 100 pF capacitance with $V_{DS} = 2\,V$ and V_{GS} set to be -0.4 V. The RF power is set to be around 0 dBm, and the LO power is around 8 dBm, such that the LO power does not exceed the maximum input power of the transistor. Furthermore, the simulated radition pattern of the CRLH LWA is shown in Fig. 5, exhibiting the frequency scanning capability.

IV. Simulation and Measurements

Fig. 6 and 7 plot the simulated IF power levels of the proposed CRLH nonreciprocal DM shown in Fig. 4. When the RF frequency is in the RH region of CRLH, as can be seen in Fig. 6, at IF frequency around 1.1 GHz, we can observe good isolation (around 13 dB) in Port 2, which agrees very well with the theoretical prediction shown in Fig. 2. On the other hand, if the RF frequency becomes in LH region, at IF frequency around 0.7 GHz, the maximum isolation happens (around 10 dB) in Port 2 which is shown in Fig. 7. It is noted between 1.4 to 1.6 GHz, which is around center frequency of CRLH, since θ_r in the transmit mode and receive mode are equal ($\beta_d(f_{RF}) \approx 0$), as shown in (4) and (6), the isolation will degrade.

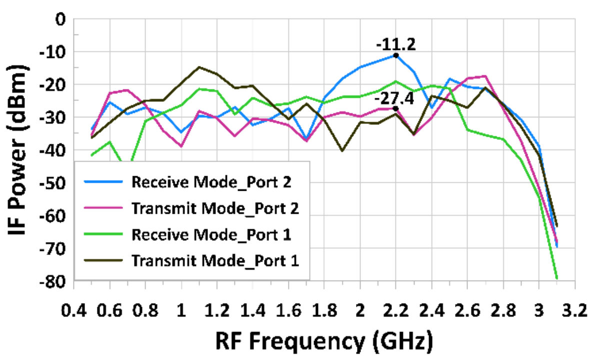

Fig. 6. Down converted (IF) power when LO = 3.3 GHz

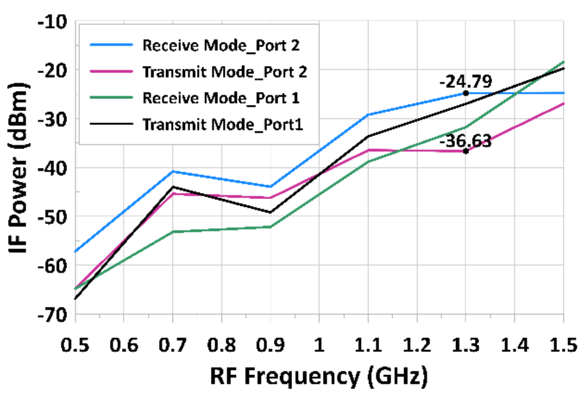

Fig. 7. Down converted (IF) power when LO = 0.6 GHz.

Fig. 9 shows the fabricated prototype, where the IF power level at the reverse port is measured in both the transmit and receive mode, in which an input power of 0 dBm is injected into Port 1 for the transmit mode and Port 2 for the receive mode, respectively. The measured isolation level is plotted in Fig. 9, where the isolation is calculated as follows:

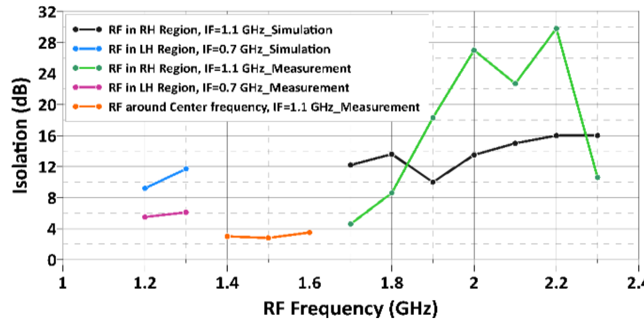

Fig. 8. Isolation at down-converted frequency (IF) in port 2 calculated based on simulation and measurement results.

$$Isolation(dB) = P_{IF-Receice\ Mode\ at\ Port\ 2}\,(dBm) - P_{IF-Transmit\ Mode\ at\ Port\ 2}(dBm)$$

As indicated in Fig. 9, by choosing an appropriate IF signal based on the LH region or RH region of RF signals, we can obtain a good amount of isolation between the transmit and receive mode thanks to the DM reverse gain at Port 2, where the receiver circuit can be connected to port 2 to extract the information from IF.

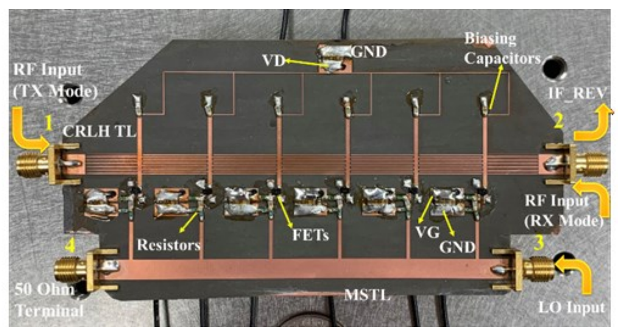

Fig. 9. Fabricated prototype of the proposed nonreciprocal DM-based CRLH LWA.

V. Conclusion

In this paper, a simultaneous transmit and receive CRLH non-reciprocal LWA based on distributed mixing principle is proposed. The LO carrier signal is injected from the gate line and is mixed with the RF signal transmitted and received by the CRLH TL in the drain line operating in fast wave region. By choosing an appropriate IF signal, in drain line reverse port, good isolation can be seen with respect to the reverse conversion gain of CRLH DM. As such, the received information can be extracted from the down converted IF signal. A six unit-cell prototype is simulated and measured to verify the isolation with respect to the down-converted IF signal for the proposed CRLH DM.

Acknowledgment

This work was supported by the National Science Foundation (NSF) under Grant ECCS-1818478, ECCS-2028823, and ECCS-2033433. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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