High-Performance Nonreciprocal RF Components with Distributedly Modulated Capacitors for Full-Duplex Radios

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***Abstract*— Nonreciprocal RF front-ends are essential for full-duplex wireless communications. Our research on nonreciprocal components designed with distributedly modulated capacitors (DMC) has found much potential in broadband, low-loss, low-noise but high-isolation transceiver front ends [1]. The design does not require magnetic materials, and thus it is also compatible with integrated circuits.**

It is a great honor for the author to be awarded with the Graduate Student Fellowship by the IEEE Microwave Theory and Techniques Society (MTT-S) in 2015. Thanks to the support, our research has moved on to the next stage where further application is found and better architecture is explored for improved performance of the DMC. In this report, two research outcomes are summarized: the first is about a nonreciprocal, frequency-tunable notch amplifier design also based on the DMC or a time-varying transmission line (TVTL); the second is about a MMIC design of the DMC for the original T/R circulator application proposed in [1] along with a balanced architecture to improve the T/R isolation over a very broad frequency range. Both topics are based on well-developed theory validated by experiments on PCB prototypes or MMIC chips. The results have been accepted and will be presented in the incoming 2016 International Microwave Symposium (IMS) held in San Francisco, CA, USA [2], [3].

***Index Terms*—MTT-S graduate student fellowship, nonreciprocal components, full duplex, time-varying transmission lines, circulators**

I. Introduction

ANUALLY, the IEEE Microwave Theory and Techniques Society (MTT-S) awards about ten graduate students around the world in the general category of microwave engineering and two in the medical applications category with the fellowships to support their research activities. It is a great honor and fortune for the author to be one of the awardees in 2015 with his research focus on nonreciprocal RF component design for full-duplex wireless communication. This report, as a final deliverable of the project that the fellowship sponsors, summarizes the outcomes of two research topics that promise the ultimate goal of high-performance nonreciprocal front-ends.

Common background of the two topics introduced in the following sections includes the time-varying transmission line (TVTL) theory and one of the TVTL's practical implementations called distributedly modulated capacitors (DMC) [1]. TVTLs can function as nonreciprocal components like circulators to suppress the interference from the transmitter to the receiver in a single-antenna, full-duplex front end. This is based on breaking the time-reversal symmetry with the time-modulation caused by the unidirectional carrier pumping into the TVTLs. Compared to the conventional ferrite circulators or other resonance-based approaches, TVTLs can achieve better TX/RX isolation over a broader frequency range with a smaller physical size. They are also compatible with integrated circuit technology. In addition to nonreciprocity, TVTLs can perform low-noise amplification with the distributed parametric gain. A TVTL can be approached by putting discrete varactors periodically in shunt with a normal transmission line. It is called distributedly modulated capacitors (DMC) to manifest the practical implementation of the TVTL.

II. A Nonreciprocal, Frequency-Tunable Notch Amplifier Based on DMC

As the parametric gain of a TVTL can compensate for the loss of the transmission line and realize an extremely high Q, by forming a feedback loop out of the TVTL, one can develop an extremely narrowband but frequency-tunable notch amplifier with high gain and low noise along with the nonreciprocity from the unidirectional carrier modulation. The DMC can be also employed to demonstrate this feature. The tunability of TVTL-based circuits can come from the sweeping of the pumping carrier frequency without changing the static biasing conditions or the physical statuses of the circuit elements or structures. A possible implementation of the TVTL-based notch amplifier is illustrated in Fig. 1, where the double-balanced DMC is employed and closed to form a feedback loop at the up-converted frequency ω_{m-s}.

A measurement on the prototype built on a Rogers board has been performed to capture the tunability of the TVTL-based notch amplifier. The prototype was based on the same recipe as the double-balanced DMC introduced in [1]. The insertion gains of the receiving path of the signals that propagate in the same direction as the carrier in the DMC are

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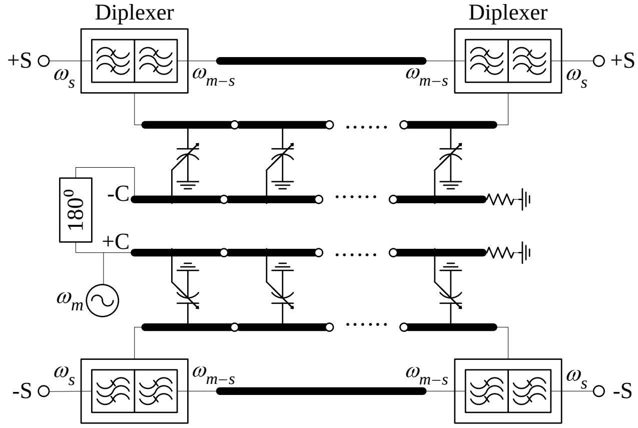
obtained by sweeping the carrier frequency from 4.8 to 5 GHz and leaving the DC bias of the varactors and carrier input power untouched. The results show an overall gain of >17 dB at the peak with a <10 MHz bandwidth at a center frequency tunable from 1.48 to 1.65 GHz. The insertion gains of the transmitting signals that travel in the reverse direction are significantly lower than the receiving insertion gains. This agrees with the nonreciprocity of the DMC [2].



(b)

Fig. 1. A TVTL-based tunable notch amplifier implemented by the double-balanced DMC [2].

III. A Broadband Parametric Circulator with Balanced MMIC DMC

A. MMIC Implementation of DMC

To develop a practical DMC for wireless applications at UHF, integration and miniaturization of the DMC must be carried out. Shown in Fig. 2 is a DMC MMIC fabricated with the 0.1 um GaN HEMT technology. The physical size of the MMIC is 9.8 mm x 1.2 mm, which is about 100 times smaller than the PCB version presented in [1].

Two DMC MMIC samples are measured and each of them achieves a RX loss less than 3 dB and TX-to-RX isolation greater than 8 dB over 0.7 ~ 3 GHz. Positive-dB parametric gain is observed in the experiment for received signals at low frequencies (<1.6 GHz) [3].

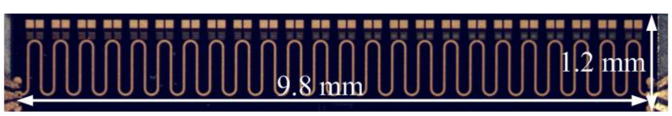


Fig. 2. Photo of the DMC MMIC realized on 0.1um GaN process.

B. Isolation Improvement – Balanced DMC

A balanced architecture of DMC [3] can be utilized to provide a significantly higher level of isolation. Here a balanced combo is built based on a pair of DMC MMICs connected with two 90^0 hybrid couplers, as depicted in Fig. 3. Measurements on the balanced DMC are conducted after the two DMC MMICs are separately evaluated. The measured RX gain drops by about 1 dB due to the loss of the couplers. However, the balanced architecture achieves about 15 dB additional isolation to that of a single DMC. The measured TX-to-RX isolation is more than 25 dB over 0.7 ~ 2.5 GHz, which covers most of the LTE bands, while the conversion loss remains to be less than 4 dB over the same frequency range.

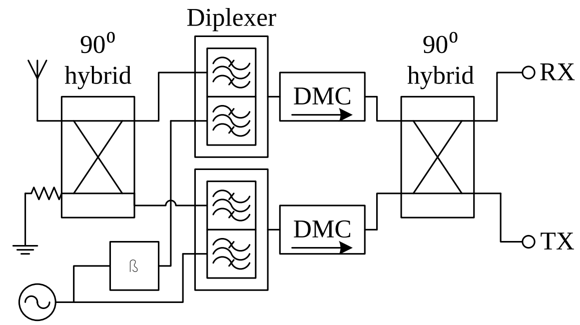


Fig. 3. Block diagram of the balanced combo of two DMC chips

IV. The Impact of the Fellowship

Given the fellowship, the author was able to reach out some industrial vendors and foundry for prototype fabrication and experimental verification. As the research was getting more efficient, the author was able to be involved in an internship with an industrial company to broaden his views in the summer of 2015. By far, the author is still unassertive in the choice between academic and industrial career, as he enjoys the excitement of both research and practical production of engineering ideas.

The author is also grateful to the sponsorship of attending IMS 2015 in Phoenix, AZ, USA, where he was able to meet many professionals, listen to high-profile technical sessions and interact with industrial exhibitors. During the conference, the author also attended and won a Student Design Competition with a team from his institute.

Acknowledgment

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