A Highly Integrated System-On-Aperture (SoA) Front-end Using Spatio-Temporal Modulation

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***Abstract*—This report briefly summarizes the research results supported by the 2024 IEEE MTT-S Graduate Fellowship Program. The project aims to develop a stand-alone, highly integrated system-on-aperture (SoA) with amplification, mixing, filtering, and radiation functionalities. This report details the implementation of the two functionalities of amplification and mixing in a cavity structure that functions as a negative-resistance parametric amplifier. The simulated results are presented using full-wave electromagnetic (EM) simulations and nonlinear circuit analysis.**

I. Introduction

Practical wireless systems have a significant amount of noise associated with them. Conventionally, the individual components in the RFFE- including antennas, filters, mixers, amplifiers, etc. - are cascaded using 50-Ω transmission line interfaces. These cascading interfaces contribute additional losses within the system, increasing the overall noise floor and reducing the range of effective communication in a crowded spectral environment [1]–[3]. In the past decade, a "co-design" approach has been widely researched to eliminate lossy interconnects between individual front-end components and improve the system's sensitivity. The co-design process is implemented by seamlessly integrating two or more functionalities into a single device. For instance, several research works have been reported on co-designed filtering amplifiers [4], filtering antennas (or filtennas) [3], [5], and active amplifying antennas [6] to improve the overall Signal-to-Noise Ratio (SNR) of the RFFE within a compact module.

The proposed project aims to push the boundaries of co-designed RF components by implementing all the essential functionalities of the RFFE within a single unit, including radiation, filtering, amplification, and frequency mixing. The following section details the design and implementation of the first building block, which integrates the mixing and amplifying functions in a cavity structure. By utilizing a varactor diode as a nonlinear, time-varying capacitor element, parametric amplification of a signal can be achieved at an up-converted frequency.

II. Concept and Implementation

The basic circuit of a negative resistance parametric amplifier consists of three tanks coupled to a time-varying capacitor at the signal frequency f_s, the pump frequency f_p, and the idler frequency f_i, as shown in Fig. 1(a) [7]. For a practical implementation, the three tank circuits can be realized within a varactor-loaded cavity, as seen in Fig. 1(b), by utilizing higher-order modes of the cavity resonator, as discussed in [8].

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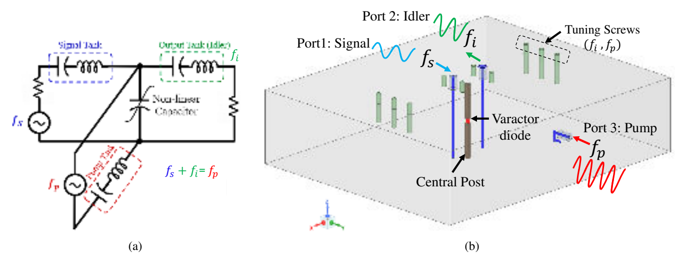

Fig. 1. (a) Simplified circuit model of a negative-resistance parametric amplifier (NRPA), and (b) Implementation of the in a varactor-loaded three-port cavity structure.

In the proposed cavity, the varactor is coupled to the TE101 mode at f_s, the TE301 mode at f_i, and the pump signal is applied at f_p, which corresponds to the TM110 mode of the cavity. The electric field distributions within the cavity and the posts supporting the varactor are shown in Fig. 2. The varactor is shown to be coupled to each of the three operating modes within the cavity, with the diode capacitance being the most sensitive to the dominant mode. The tuning screws, as seen in Fig. 1(b) are used to tune the TE301 mode at idler frequency and the TM110 at pump to achieve the sum frequency relationship of $f_s + f_i = f_p$, which is one of the conditions imposed by the Manley-Rowe relations to enable parametric amplification [7]. The coaxial feed ports for the signal and idler ports are located on the top cavity wall, while the pump is fed through a magnetic loop on one of the side walls of the cavity, as seen in Fig. 1(b). Since the pump signal is much larger than the applied RF signal at f_s, the pump input position is optimized to ensure maximum isolation from the signal and idler ports.

III. Results and Discussion

The S-parameters of the three-port cavity structure are shown in Fig. 3 for the HFSS simulated model and the ADS simulation, which show close agreement. The signal frequency is 880 MHz, the output or idler frequency is at 4.14 GHz, and the pump is applied at the sum frequency of approximately 5.014 GHz. The pump-signal and pump-idler isolation curves, indicated by S_{32} and S_{31} respectively, show a pump power suppression of 15 dB at the idler and 27 dB suppression at the signal frequencies.

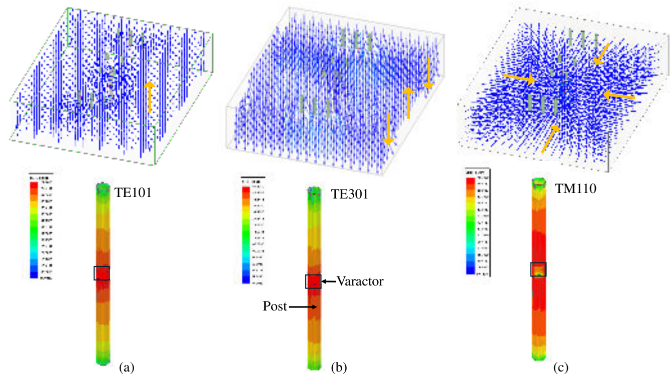

Fig. 2. Electric Field distributions from HFSS Eigenmode simulations within the cavity and on the posts supporting the varactor, for three modes at signal (TE101), idler (TE301), and pump (TM110).

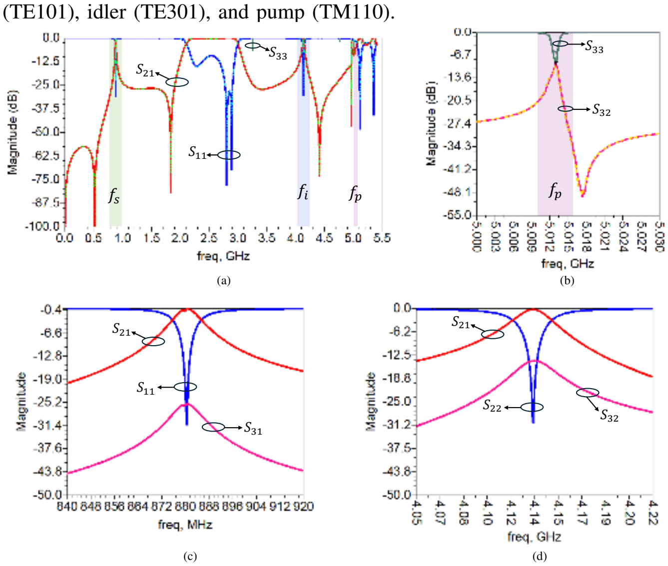

Fig. 3. S-parameter simulations of the three-port cavity in HFSS (solid line) and ADS (dotted line). (a) S-parameters across full frequency band of operation, (b) at pump, (c) at signal, and (d) at idler (output) frequency.

Next, a harmonic balance (HB) simulation is performed in ADS with the built-in nonlinear capacitor model, as seen in Fig 4. The applied pump power is 19 dBm, and a signal power of -47 dBm is provided through port-1. Through the mixing action of the diode, a gain of 24.3 dB is observed at the idler frequency and 22 dB at the signal frequency. Note that the load resistance at idler prt, R_L, is tuned to 4 Ω to maximize the gain of the negative-resistance parametric amplifier. As seen in Fig. 4, the pump power at the output is suppressed by around 10 dB due to the inherent modal isolation. The pump power can be further suppressed at the load by using high-rejection pump filters.

Future work will investigate coupling mechanisms of the negative-resistance cavity with a slot antenna to enable the radiation of the amplified signal at the idler through the slot aperture. The slot antenna will also function as the second resonator of a bandpass filter, thereby integrating a filtering response within the amplifying, mixing, and radiating unit.

CONCLUSION AND CAREER PLANS

I am currently considering future career paths in both academia and industry research roles. The MTT-S fellowship

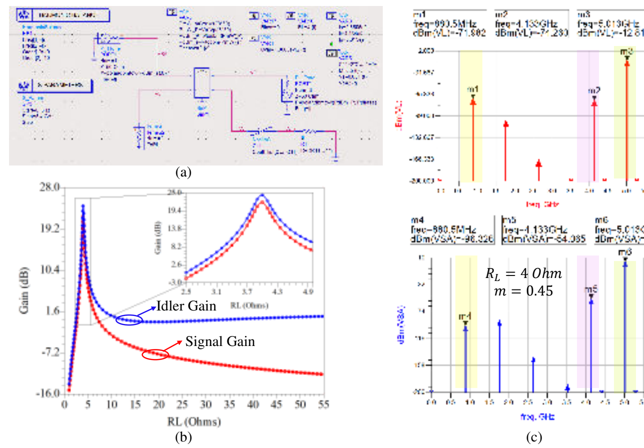

Fig. 4. (a) ADS schematic for the 3-port NRPA cavity structure of Fig. 1(b). (b) Signal and idler gains as a function of the load resistor (R_L) at output port, and (c) power spectrum at the input and output port for $R_L = 4\Omega$.

support and the proposed project have helped me refine my specific areas of interest in designing integrated front-end modules with passive and active device circuitry. My visit to the IMS 2024 conference in Washington, D.C., was a great learning and networking opportunity. I want to thank MTT-S and IEEE for their continued support and opportunities for graduate students to pursue their research in RF and Microwave Engineering. As the chapter chair of the MTT-S student-branch chapter at OU, I am trying to get more students interested in the research fields covered by MTT-S. My future plans also include being an active member of IEEE and MTT-S in as much capacity as possible to contribute, progress, and support the state-of-the-art research conducted in this field.

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