Tunable Multiband Power Amplifier using Thin-Film BST Varactors for 4G Handheld Applications

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***Abstract*— A new methodology for multiband tunable power amplifiers (PA) using barium-strontium-titanate (BST) varactors is presented. A prototype tunable power amplifier has been developed and its performance is evaluated in context of the upcoming 4G scenario which demands for multi-mode/multiband power amplifiers capable of operating over multiple frequency bands. The tunable PA requires two tuning voltages at the output matching network as well as an additional tuning voltage for a novel tunable 2^nd harmonic termination. The PA is continuously tunable from 1700 to 2300 MHz, covering multiple bands. Tunable PA measurements with LTE signals show a maximum gain of 27dB with Pmax of 24.1dBm and an EVM of 6% using BST varactors having Q-factors not more then 30 at sub-2GHz frequencies.**

***Index Terms* — Tunable, Multiband power amplifier, BST varactors, 4G.**

I. Introduction

4G is a term [1] describing the undergoing evolution of mobile radio communications redefining the way how we communicate, shape cultures and impact the societies across the globe. 3GPP LTE is a 4G-frontrunner in defining 4G along with its features such as frequency bands and specifications.

Reconfigurability or tunability is a highly demanded trait [2] of the RF Front end of a handheld device, which complies with LTE in order to reduce the number of components required for separate signal paths dedicated for each band of operation. This would clearly result in decrease in cost, size and energy consumption.

In this paper a new methodology for tunable PA is presented, which achieves excellent tuning capability while complying state of the art LTE signal requirement. After a brief note on reconfigurable and tunable PA topologies in section II, BST varactors are introduced with explanation on their functionality in section III. Section IV discusses the design and simulation of the proposed tunable PA. Prototype tunable PA implementation is presented in section V followed by section VI showing prototype measurement results.

II. Reconfigurability and Tunability

It is much more desirable to have single multimode/ multiband PAs that would fulfill the requirements of operating over multiple frequency bands rather then having multiple PAs each operating on a specific frequency band. The concept of a single multiband PA offers numerous advantages in terms of size, number of components, energy consumption and cost of front-end modules of handheld devices, especially for 4G applications.

The concept of multimode/multiband PA can be realized by incorporating reconfigurability or tunablity in the PA itself. Noticeable PA module topologies that promise to meet the demands of power amplification with multi-frequency band coverage in accordance with the upcoming 4G standard are: (1) unit selection topology, (2) broadband topology, (3) distributed topology, (4) band reconfigurable topology, and (5) multiband matching topology. PA modules based on the unit selection topology have the advantage of high effeciency and the ability to be designed with standard methods [3] but they suffer from the requirement of an additional PA for each band.

Balanced and broadband amplifiers are good candidates [4] to meet broadband requirements but so far their deployment is not practical at low GHz frequencies used in typical handset wireless communication systems as they notably suffer either from the requirement of the quarter wavelength size of couplers or from showing low effeciency and relatively large chip size.

PAs with band-reconfigurable topologies have good efficiencies and require a single amplifying device [5], which is another advantage, but the requirement of voltage control and a large number of matching elements are its drawbacks. PAs with multiband matching topologies [6] have a clear advantage of single device and higher effeciency, but suffers from requirement of large number of matching elements.

It is well established that electronically tunable subsystems can function optimally when conditions such as frequency of operation changes [7]. Depending on the specific circuit where such tunable components are used the results may have lower cost, smaller size, an improvement of battery life time and show increased performance. Electronically tunable systems can be designed by using various technologies such as MEMS, ferroelectric devices, solid state devices, diodes, inductors and capacitors. Among them, electrical tuning of a capacitor is the simplest and most common choice for making tunable matching circuits.

III. BST VARACTORS

BST ($Ba_{1-x}Sr_xTiO_3$) varactors are important for their application in frequency agile tunable microwave circuits. They are broadly classified as thin and thick film devices having an electric field dependent dielectric permittivity. BST varactors have an excellent tunability, reliability and operating voltage characteristic, but suffer from lower quality factors at higher frequencies of operation.

As derived in [8] the capacitance of the varactor can be described by the following expression:

$$C_{BST} = \frac{C_o - C_f}{2\cosh\left(\frac{2}{3} ar\sinh\left(\frac{2V}{V_{\frac{1}{2}}}\right)\right) - 1} + C_f \quad (1)$$

where C_o is the capacitance at 0 volts, C_f is the fringing capacitance, and $V_{1/2}$ is the voltage where $C(V_{\frac{1}{2}}) = C_o/2$.

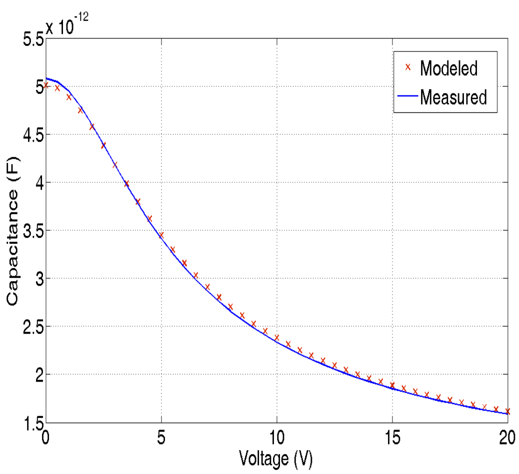

Fig. 1. Comparison between the measured and modeled [8] capacitance of a BST varactor for different bias voltages.

Fig. 1 illustrates the voltage dependence of BST varactors with a zero bias capacitance of 5pF. The capacitance C_{BST}, as well as the varactor quality factor Q, have been extracted from the measured input admittance Y which can be defined as:

$$C = \frac{\mathrm{Im}\{Y\}}{2\pi f} \quad (2)$$

$$Q = \frac{\mathrm{Im}\{Y\}}{\mathrm{Re}\{Y\}} \quad (3)$$

The tunability exceeds 60% at a bias voltage up to 20 volts and a quality factor of $Q \approx 30$, measured in the frequency region around 2GHz.

IV. TUNABLE PA DESIGN AND SIMULATION

RF PA models from Triquint Semiconductors were used in the study along with BST varactor models and system level investigations were done for tunable matching networks to have an insight on gain, power, spectral emission and linearity of a tunable PA.

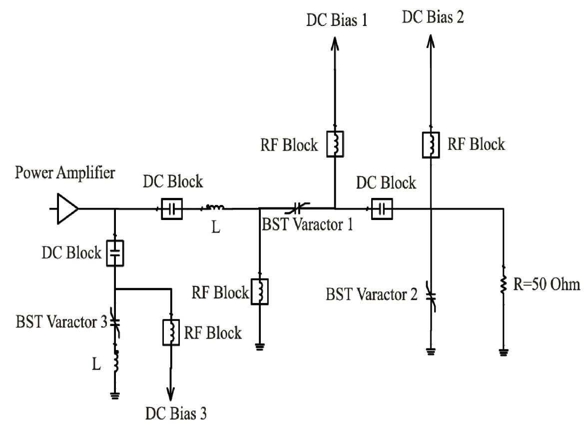

Fig. 2. Schematic of PA with tunable output matching and second harmonic termination.

Fig.2 shows the schematic of a PA with an L-type match comprising BST varactors. Two bias voltages (DC Bias1, DC Bias 2) are used to tune the BST varactors which change the output impedance seen by the PA. With the varied impedance matching, the PA is configured to operate at different frequencies.

A novel idea of a tunable 2^{nd} harmonic termination is a part of design. A third bias voltage (DC Bias 3) is employed to tune the BST varactor to provide a second harmonic termination in accordance to a suitable frequency on which the PA operation is configured, which can enhance its effeciency.

V. PROTOTYPE TUNABLE PA IMPLEMENTATION

The previously discussed tunable PA was implemented on prototype boards fabricated based on Rogers RO4003C substrate with h=0.2mm and ε_r=3.55 as illustrated in Fig. 3. The footprint of the circuit consists of TQM676021 PA die from Triquint Semiconductor, 0402-series SMD components and the BST varactors from EPCOS. The PA die is bond-wired because a similar version of die was used in our simulations and the BST varactors were assembled in a flip-chip procedure in order to minimize the interconnection parasitics and the associated loss mechanisms at higher frequencies.

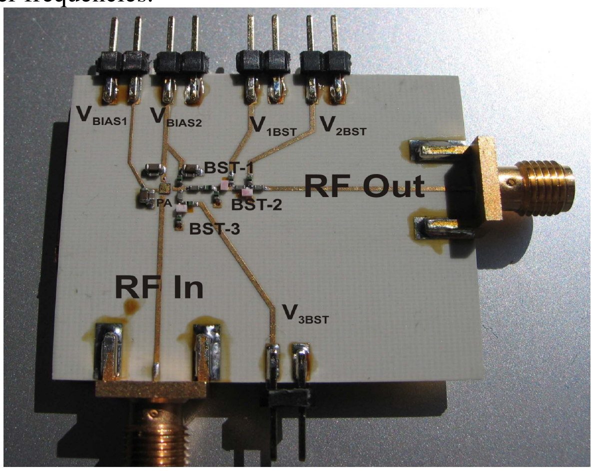

Fig. 3. Fabricated prototype tunable PA board.

VI. MEASUREMENTS

All S-parameter measurements were taken with a Rohde&Schwarz ZVB8 vector network analyzer. The varactor tuning at the output matching with appropriate voltages affects its capacitance, thus changing the output matching characteristics of the PA. This in turns tunes the operation of the PA at different frequency bands.

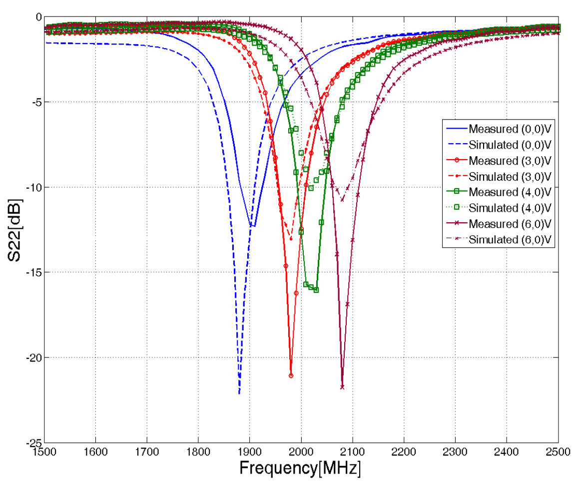

Fig. 4. Measured and simulated output reflection coefficients of tunable PA at different bias states.

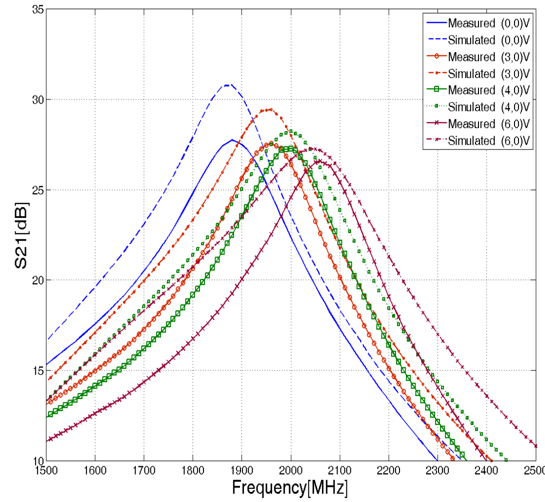

Fig. 5. Measured and simulated transmission coefficient of the tunable PA at different bias voltages.

Figs. 4 and 5 display simulation as well as measurement results for the output reflection and transmission S-parameters at different bias voltages applied across the varactors. The experimental and the simulation results are in good agreement except the increased losses observed at lower-band frequencies which can be associated to the inaccuracies in the description of models used in the simulations.

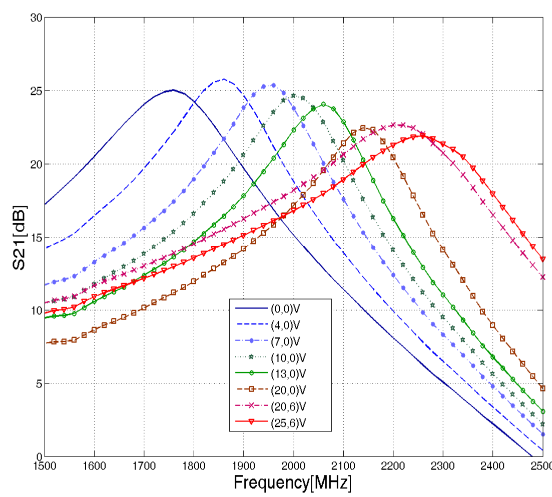

Fig. 6. Measured S_{21} of tunable PA for bias voltage combinations from 0 to 25 volts.

Fig. 6 shows the extent of tuning of another board variant with a tuning range from 1700 to 2300 MHz, when two bias voltages were applied and tuned from 0 to 25

TABLE I

Frequency (MHz)	Gain (dB)	Pout (dBm)	EVM (%)	ACLR (dB)			
				Adjacent Lower	Adjacent Upper	Alternate Lower	Alternate Upper
1800	27.6	20.5	6.9	51.3	50.8	71.9	73.8
1950	26.5	22.6	6.6	52.6	53.3	72.5	69.5
2100	26.3	24.1	4.8	54.1	58.9	69.0	66.7

volts applied across the BST varactors. Fig. 7 illustrates the feature of the tunable 2nd harmonic termination. With an application of a proper bias voltage, the second harmonics can be appropriately terminated while simultaneously tuning the PA frequency of operation.

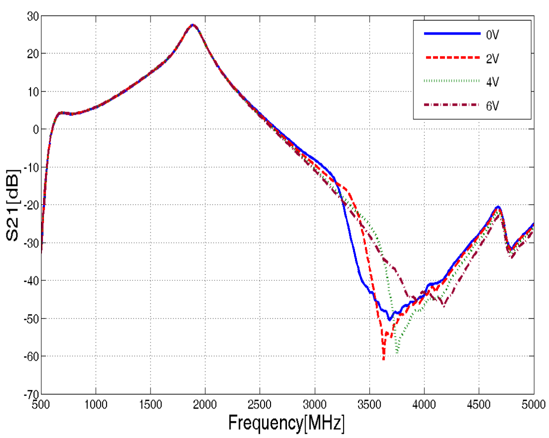

Fig. 7. Measured S_{21} for the PA at different bias states for 2nd harmonic termination.

Table I represents the measurement results of the tunable amplifiers at various center frequencies using an LTE carrier setup of 20 MHz, 16QAM (100 resource blocks). The noticeable difference between upper and lower ACLR values is due to the nonlinearities of the BST varactors. The presented measurement results are attained without a duplexer; its inclusion will leave closer margins for the PA performance in an RF front-end.

VII. Conclusion

Tunable PAs based on BST varactor have been discussed. The principles of a BST varactor and a tunable PA are explained. The design and implementation of tunable PAs is illustrated along with measurement results. The implemented PA demonstrates its tunability over the frequency range from 1700 to 2300 MHz, and compliance with the LTE signal requirements within a frequency range of 1800 to 2100 MHz.

Acknowledgement

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