Reconfigurable Three Functional Dimension Single and Dual-Band SDR Front-Ends Using Thin Film BST-Based Varactors

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ABSTRACT

This paper presents a performance evaluation of single and dual-band software-defined radio (SDR) front-ends using commercially available barium strontium titanate (BST) thin film to control SDR receivers dynamic range and mitigate interference. Firstly, an SDR front-end solution using a BST-based single-band bandpass filter (BPF) is developed to manage in-band attenuation according to the input power. Secondly, a dual-band SDR front-end to avoid high power interference with its spectral content on the below side of the second band is designed. This device is performed with a BST-based dual-band BPF providing independent control of the power limiting capabilities of the first and second bands. The BST component introduces a dependence on bias voltage, frequency, and input power. Consequently, by applying a 0 V bias, it is possible to target interferers between 700 MHz up to 1 GHz and attenuate them more than 7 dB at 40 dBm. The frequency dependence is defined by the second band, which retains its filtering performance while performing interference cancellation in the first band. This SDR solution implements a three functional dimension device in the upper MHz with a power-dependent insertion loss, high threshold power level, and frequency selectivity.

INDEX TERMS

Dual-band bandpass filters, ferroelectric devices, frequency selectivity, intermodulation distortion, nonlinear measurements, power limiters, SDR front-ends, three functional dimension devices, tunable microwave filters.

I. INTRODUCTION

Miniaturized and reconfigurable radio-frequency (RF) front-ends are increasingly being developed to accommodate new wireless communications systems for satellite and mobile communications, as well as radar applications.

Due to wireless communications open nature and the rapid development of software-defined radio (SDR), the quick access to available interference devices with common bands and services became a threat for both civil and military communications [1], [2]. These devices can easily decrease the signal-to-interference-plus-noise ratio by employing radio jamming to disrupt communications. There is a call for multioperability, multiband, and power limiting capabilities to mitigate the effects of RF jamming and interference [3]. As a result of this necessity, one of the most promising solutions for enabling new hardware for next-generation high-frequency systems is the construction of sophisticated enhanced-performance RF components.

While the term SDR has traditionally referred to a programmable software stage implemented in a field-programmable gate array (FPGA), the fixed set of RF hardware raised interest due to its lack of adaptability. The applications of SDR cover frequency bands from 730 MHz to 6 GHz.
However, hardware ultimately limits the applicability of the systems. These systems tend to be designed using high-order filters or notch filters that isolate a portion of the spectrum of interest. Nevertheless, these filters either limit the flexibility of the system or receive much of the spectrum, which is therefore susceptible to interference [4], [5].

The upcoming devices include adaptive microwave (MW) filters and power limiters as major components. These critical RF blocks enable wireless systems to effectively reject out-of-band power-frequency-agile interference and noise by performing signal-band selection processes. Switchable band control devices, [6], tunable barium strontium titanate (BST) based filters, [7], [8], tunable RF bandpass filter (BPF) for interference suppression, [9], and notch filters, [10], have been one of the most popular research subjects in recent decades.

A glance towards power limiters and frequency selective limiters (FSLs) is just as important. Frequency selection avoids the problem of losing weak signals in the presence of a strong signal in SDR systems by attenuating only those signals in designated frequency bands, as illustrated in Fig. 1a). Large-scale research has been done in the field of anti-jamming solutions. The Hyper-wideband Enabled RF Messaging (HERMES) program from Defense Advanced Research Projects Agency (DARPA) seeks advanced systems and techniques for jam-resistant RF communications that allow adaptive filtering to operate in the presence of jamming and interference. In broadband receivers, high-power limiters are required due to the restricted power capability of diodes and the frequency selective features [11]. Allowing new techniques to modify the input gain to maintain the dynamic range of analog-to-digital converters (ADCs) in the presence of large input signals is as critical as preventing signal damage.

Existing hardware solutions for resolving interference issues and controlling dynamic range rely on input power-dependent materials with distinct power threshold levels [12]–[14]. New devices known as FSLs were developed by incorporating ferrite materials such as yttrium iron garnet (YIG) to select transmission and receiving signals based on input power levels [15]. Ferrite based devices presents low input power threshold, [16], [17], dependence on the line width, [18], and low tuning speed [19], [20]. The applications of such FSLs to maintain the dynamic range of RF receivers require a strong DC-magnetic field in a monolithic microwave circuit (MMIC) configuration. Previous works, such as [21], address limiting the output power with a threshold level of -20 dBm with the primary goal of resolving interference issues in low power systems. In [22], it was outlined the characteristic of ferromagnetic-based limiters in the presence of multiple signals. One of the main applications would be using such a limiter before a broadband MW receiver in small-signal scenarios. The referred FSLs works explore the power absorption as a unique characteristic of ferromagnetic materials and present a range of power threshold levels from -20 dBm to 10 dBm. This paper focuses on the use of ferroelectric components to achieve power limiting capabilities with high-power threshold levels ranging from 20 dBm to 40 dBm.

The nonlinear behavior of ferroelectrics has been described for several years, and the new material technologies admit them to stand out. Firstly, in [23], frequency selectivity is demonstrated by using a ferroelectric material. Still, the ferrite devices disadvantage was reported, consisting of a necessarily strong biasing DC magnetic field to perform tunability. Ferroelectric power limiters employ the RF field dependency of the dielectric constant to achieve power limiting capabilities. This RF field dependency may be exploited to achieve frequency tuning and power-dependent insertion loss (IL). The electric field applied changes the permittivity and loss tangent of the ferroelectric material, resulting in a nonlinear change of capacitance and MW conductance. Since the IL of the main transmission line is a function of mismatch, a shunt stub made of transmission lines loaded by a nonlinear ferroelectric varactor can provide attenuation controlled by the input power.

Ferroelectric materials, such as BST, were reported to present nonlinear behavior while applying high input power levels. In [24], a BST varactor-tuned in a range of bias voltages is proved to possess nonlinear behavior. Furthermore, and more importantly, the nonlinearity is dependent on the properties of the BST film. In [25], the nonlinear behavior of the BST film is characterized by applying different bias
voltages. Similar to other works, when the BST films are biased at 0 V, it reveals stronger nonlinear effects. In this case, the device only displays nonlinear behavior when the input power is over 10 dBm. The nonlinear analyses in [26] and [27] mainly address small-signal excitations through the third-order intercept point (IP3) measurements, which limits its applicability to high-power jammers. One of the goals of this work is to explore high-power anti-jamming circuits in an SDR scenario. For the first time, BST commercial components are implemented in RF devices not only to perform tunability but to confer power limiting capabilities to control dynamic range and avoid jamming interference.

This work aims to develop a three-functional dimension (3fD) device that achieves an adaptive response in wideband operation depending on input power. It also has the advantage of limiting the output power to a specific operating frequency band without interfering with other equipment frequency bands, as shown in Fig. 1b. The 3fD device has an IL response dependent on bias voltage, frequency, and input power. The ferroelectric-based SDR front-ends include this new device, distinguishing themselves in the threshold power levels and bias voltage control, compared to the ferrite-based FSLs. Consequently, 3fD devices can be used as power limiters when higher threshold levels are required. Most importantly, this work demonstrates the possibility of using input power and bias voltage correlation to reconfigure single-frequency and dual-frequency SDR front-ends, Fig. 1c.

This paper is organized as follows. Section II covers the BST nonlinear model based on the DC component response, the simulation and characterization regarding the input power response, and the synthesis of the single and dual-band SDR front-ends. The SDR front-end solutions based on a single-band BPF are then described in Section III. The single-band BPF with central frequency at 900 MHz is designed and tested according to the IL dependent on voltage and input power. In addition, a second-order Chebyshev dual-band BPF with center frequencies of 780 MHz and 3.5 GHz is implemented in Section IV. Its capability of frequency selectivity is synthesized and measured by performing one-tone characterization in both center frequencies. Section V displays the new 3fD device. Both the commercial BST technology and the dual-band SDR front-end allow the design of the 3fD device that is characterized by the IL dependence on input power, center frequency, and bias voltage. Lastly, in Section VII, this paper is concluded with some future work suggestions.

II. SINGLE AND DUAL-BAND APPROACH IN SDR FRONT-ENDS

The following section contemplates the details of the synthesis and design that implement BST thin film components in state-of-the-art RF filters for SDR front-ends. It proposes joining the use of traditional topologies with commercial BST technology and explaining how the center frequencies and bandwidth are computed in each filter. The implementations contemplate the design of:

- a single-band BPF to control the dynamic range in SDR applications. Due to the BST component dependency upon the input power and bias voltage, a high-power FSL is performed.
- a dual-band BPF to show the possibility of canceling interference in selected bands while keeping the filtering features of other operating bands in the same SDR frontend. A first band placed at 780 MHz represents a mask for the interference profile with its spectral content on the below side of the second band, 3.5 GHz.

A. BST CAPACITANCE NONLINEAR MODEL BASED ON DC COMPONENT RESPONSE

Adaptive RF devices are created by tuning capacitance or inductance. Ferroelectric materials, such as BST, may provide high tuning, high-power handling capabilities, and an IL compression dependent on the input power. The BST thin film capacitors used in this work, STPTIC-15G2 from STMicroelectronics, are a suitable candidate in the upper MHz range to design adaptive and power-dependent SDR front-ends. The nonlinear BST thin film model presented in this paper is based on S-parameters measurements over a range of bias voltage. This characterization allows the calculation of the nominal capacitance for a range of frequencies from 700 MHz to 1.5 GHz [28]. The capacitance characterization of the BST thin film component in shunt topology is displayed in Fig. 2. The capacitance nominal value of STPTIC-15G2 manufacturer’s datasheet regarding the input bias voltage is compared with the measurement results. The capacitance value is described as a function of voltage, (1), and the simulation results of the manufacturer’s model have not represented accurate results when compared to the measurement results, Fig. 2. The model was implemented in Agilent Advanced Design System (ADS) to perform linear and harmonic balance (HB) simulations. A wideband characterization from 700 MHz to 1.5 GHz allows a more accurate BST-based circuits simulation model.

\[
Cap_{\text{manufacturer}}(V) = \left(2 - (4E^{-1} \ast V) + (4E^{-2} \ast V^2) - (2E^{-3} \ast V^3) + (5E^{-5} \ast V^4)\right)pF
\]  

(1)

In a first approach, to evaluate the nonlinear behavior of the commercial BST component and using the measurement results from Fig. 2, a voltage-dependent polynomial equation is extracted for 780 MHz and 900 MHz, Fig. 3. The selected bands are the center frequencies of the SDR front-ends developed in this work.

The capacitance value is described as a function of voltage, V, for 780 MHz and 900 MHz in (2) and (3), respectively. It is applied a range of bias voltage between 0 V and 10 V to the BST thin film in shunt topology.

This model was used in ADS to aid the synthesis and simulation of the single and dual-band SDR front-ends. The analytic expressions describe the nonlinear component in the
linear simulation to test the circuits tunability. The tunability is calculated and measured by evaluating the minimum and maximum frequency bands regarding the range of bias voltages applied.

\[ Cap_{780MHz}(V) = (2.25 - (8.2E-1 * V) + (4.9E-1 * V^2) - (1.9E-1 * V^3) + (4.4E-2 * V^4) - (5.6E-3 * V^5) - (3.7E-4 * V^6) - (9.7E-6 * V^7)) \, pF \] (2)

\[ Cap_{900MHz}(V) = (2.19 - (7.2E-1 * V) + (4.6E-1 * V^2) - (1.9E-1 * V^3) + (4.5E-2 * V^4) - (5.8E-3 * V^5) - (3.8E-4 * V^6) - (1.02E-5 * V^7)) \, pF \] (3)

The HB simulations allow the test of IL compression regarding the input power with the frequency as a parameter.

**B. BST NONLINEAR CAPACITANCE SIMULATION AND CHARACTERIZATION BASED ON INPUT POWER RESPONSE**

In Fig. 4, the HB simulation and the one-tone characterization of a BST thin film in shunt typology are displayed. Using CW signals with center frequencies of 780 MHz, 900 MHz, and 2.5 GHz, the component is characterized and simulated regarding a range of input power from 0 dBm to 40 dBm. The model is tested regarding the bias voltages of 0 V, 3 V, and 10 V. As a result, the accuracy of the model is tested regarding the center frequency and the bias voltage.

Between 750 MHz and 900 MHz, the power limiting capabilities of the BST thin film are particularly prominent. Up to 20 dBm, the polynomial model delivers accurate results. The linearity of a single BST thin film increases when higher bias voltage is applied. When applying a 0 V bias, it presents a threshold power level of 30 dBm and an IL compression of almost 2 dB and 1.5 dB for the simulation and measurement results, respectively, Fig. 4a).

The main difference between simulation and measurement results occurs when applying a bias voltage of 3 V, as seen in Fig. 4b). The nonlinear model lacks accuracy when compared with the measurement results between 25 dBm and 35 dBm. This phenomenon is discussed in Section III, which addresses memory effects. On one hand, the simulation results show that the component has a threshold power level of 35 dBm and an IL compression of nearly 1 dB. The power limiting capabilities, on the other hand, are not reflected in the measurement result. Although the model is imprecise at 3 V bias, the IL compression diminishes at higher bias voltages, as observed in Fig. 4c). Regarding any bias voltage, the component operates as a linear capacitor in the upper range of 2.5 GHz, with no tuning range or IL compression. As a result, in Section IV, the second band of the dual-band SDR front-end is fixed even when the bias voltage is varied between 0 V and 10 V. The analytic polynomial model proposed in this paper accurately describes the nonlinear
behavior in small-signal. The deviation of the model with the HB method increases with the input amplitude if higher order harmonics and intermodulation products are considered.

C. SINGLE-BAND BANDPASS FILTER SYNTHESIS

The primary goal of developing a single-band BPF is to construct a single-band SDR front-end that can be used for jamming interference cancellation and ADC dynamic range control. The implemented device relies on a BPF design, which can be found in [28], and a tunable bandpass filter (TBPF) consisting of the inductance, \( L \), and the capacitor, \( \text{Cap}(V) \), as shown in Fig. 5. The capacitance value fluctuates with bias voltage, \( \text{Cap}(V) \), providing the circuit tunability.

At the beginning of this approach, a stepped impedance low-pass filter is realized in a series combination of high-pass and low-pass impedance sections of microstrip lines. The proposed stepped impedance low-pass filter is transformed into a BPF using \( \lambda/8 \) short-circuited stubs. At this stage, the BPF filters allow for a narrower band and a higher order filter design.

The additional shunt BST components vary the resonance by introducing a dependence on its own capacitance, and as a result, alternative short-circuited stubs are calculated by setting a cutoff frequency, \( f \), and a modulated capacitance value, \( \text{Cap}(V) \), as shown in Fig. 3. So, the resonance is given by:

\[
2\pi f = \frac{1}{\sqrt{L \cdot \text{Cap}(V)}} \quad (4)
\]

where \( V = 0 \) for the prototyping development, and the capacitance value is approximately 2 pF at \( f \) between 750 MHz and 900 MHz. The inductance value, \( L \), can be calculated using (4). By obtaining the lumped value of the desired inductance, the equivalent short-circuited stub length, \( l \), can be calculated at last:

\[
l = \frac{\sqrt{v_0 L}}{120\pi} \left[ \frac{w}{h} + 1.393 + 0.667 \ln \left( \frac{w}{h} + 1.444 \right) \right] \quad (5)
\]

where \( w \) is the line width considering a 50 \( \Omega \) line impedance. Using the above-mentioned approach, it is possible to construct single-band TBPFs with a defined center frequency to be used in adaptive SDR front-ends. Section III describes the circuit calculations.

D. SECOND-ORDER CHEBYSHEV DUAL-BAND BANDPASS FILTER SYNTHESIS

To develop the 3fD devices dependent on frequency, bias voltage, and input power, we propose using a class of dual-band BPFs based on miniaturized stepped impedance resonators (SIRs), where these SIRs are coupled by alternative inverters. The SIR structures presented are independent and admit many dual passband designs because their own structure determines the resonant frequencies and reactance slopes.

This work holds designs and measurements for a second-order Chebyshev dual-band BPF based on the miniaturized SIRs coupled by two alternative inverters, \( K \), with the additional components of commercial BST thin films. The added components affect the \( \lambda/4 \) SIR reactance slope ratio versus the first two resonant frequencies ratio. The schematic of a SIR, which consists of two impedance sections, \( Z_1 \) and \( Z_2 \), with electrical lengths \( \theta_1 \) and \( \theta_2 \), respectively, is presented in Fig. 6. As a second-order filter, the left-end of \( Z_1 \) is short-circuited, therefore the dual-band BPF is designed according to [29], but considering the modifications that the new component introduces into the mathematical model of the filter. The initial resonator reactance slope of a tuned resonator is predicted to change according to the graphical model shown in Fig. 3, becoming dependent on the BST component reactance, \( X_{\text{BST}} \). The second-order implementations only need one \( K \) inverter. The effect of the reactance dependency of voltage impacts the calculations of the alternative inverters \( K \). The direct impact of the BST component in the inter-resonator \( K \) coupling degree can be expressed as:

\[
K_{n,n+1} = \frac{FBW \cdot X_{\text{BST}}}{\sqrt{8n8n+1}} \quad (6)
\]

where \( FBW \) is the fractional bandwidth and \( g_n \) and \( g_{n+1} \) are the normalized elements in the low-pass filter prototype. The coupling degree can be calculated according to [30]. The K value of a metallic via monotonically increases with frequency. Analog to [29], the diameter of the metallic via of the designed filter shown in Fig. 6 is chosen as 0.6 mm.

Fig. 6 shows the schematic of a \( \lambda/4 \) SIR, which consists of two impedance sections, \( Z_1 \) and \( Z_2 \), with electrical lengths...
of $\theta_1$ and $\theta_2$, respectively. The left end of the section is short-circuited by the structure that involves the $K$ inverter described previously, and due to that, the impedance, $Z_{in}$, can be obtained by:

$$Z_{in} = jZ_1 \frac{21}{27} \tan \theta_1 \tan \theta_2 - 1 \frac{21}{27} \tan \theta_2 + \tan \theta_1. \tag{7}$$

According to the resonant condition, implicated in Fig. 6, and by assuming an ideal short-circuit, $Z_1 + Z_{in} = 0$, the numerator in (7) is equal to zero. So, if the first resonance mode is $f_0^I$, and the second one is $f_0^II$, the latter is ideally described as:

$$R \tan(k \theta_1) \tan(k \theta_2) - 1 = 0 \tag{8}$$

where $k$ is equal to $f_0^1/f_0^II$. The reactance $x_{in}$ of the $\lambda/4$ SIR for both resonant modes is derived by:

$$x_{in} = \int \frac{f}{2} \frac{dx_{in}}{df} \left|_{f=f_0^I}^{f=f_0^II} \right. = \frac{Z_1}{2} \theta_1 \sec^2 \theta_1 + R \theta_2 \sec^2 \theta_1 \sec^2 \theta_2 + \frac{R^2 \theta_1 \sec^2 \theta_1 \tan^2 \theta_2}{(R \sec \theta_2 + \tan \theta_1)^2}. \tag{9}$$

The details of the $\lambda/4$ SIR to be investigated and the de-embedded $K$ inverters are presented in [29]. Lastly, as the matching network, this design includes a dual-frequency transformer divided into two sections described in [31]. Section IV describes the circuit calculations.

III. SDR FRONT-END: SINGLE-BAND APPROACH

A single-band BPF with a projected center frequency ranging from 900 MHz to 1.05 GHz and a fractional bandwidth of 15% was realized using a Rogers 4350 laminate with a thickness of 0.762 mm and a dielectric constant of 3.66, as shown in Fig. 7. The filter impedance is 50 $\Omega$, the highest practical line impedance is 120 $\Omega$, and the lowest one is 20 $\Omega$. This filter is based on the circuit model presented in Fig. 5. The stub length $L2$, Fig. 7, is determined using (5), which accounts for the contribution of the BST varactors, with $l = L2 = 21$ mm.

To evaluate its tunability and nonlinear features, the device employs two BST thin film varactors in shunt configuration. As demonstrated in Section II, the BST tunable varactors are characterized by a polynomial function that links the nonlinear capacitance and voltage. Using this single-band BPF, the power limiting capability of these devices was first investigated.

A. INSERTION LOSS AND TUNABILITY

The BST-based filter tunability over frequency simulation and measurement results are presented in Fig. 8. The capacitance reverse exponential growth is emphasized in these results due to the large frequency tune from 0 V to 3.8 V and the lower frequency tune from 3.8 V to 9.9 V. Two BST thin film varactors with a capacitance range from 0.6 pF to 2.19 pF are applied to tune the filter center frequency. One can observe a center frequency tuning in a band range between 906 MHz and 1.041 GHz. The return loss varies over the tuning range from 27 dB to 17 dB between 906 MHz and 1.041 GHz. This is due to the filter fluctuating impedance as a result of its tunable characteristic design. The transmission coefficient increases from 3 dB to 1.5 dB between 906 MHz and 1.041 GHz. This BST-based device is suitable as a tunable filter for operation in the desired band.

The nonlinear properties of the filter are discussed in the following two sections, where the results of one-tone and two-tone characterizations are analyzed. The one-tone tone characterization was a test selected to outline the insertion loss compression in the center bands of the filters where the models of the BST components were specified, 780 MHz and 900 MHz. However, this test does not reveal significant information about distortion in MW circuit. Consequently, the two-tone characterization enables the study of nonlinearity and memory effects.

B. ONE-TONE CHARACTERIZATION AND INTERMODULATION DISTORTION MEASUREMENTS

The nonlinear distortion of the single-band BPF can be analyzed by one-tone characterization to obtain the AM-AM compression curves. One-tone characterization of the BST-based filter has been performed using a signal generator, SMW200A, connected to an FSW analyzer from Rohde & Schwarz (R&S), as shown in Fig. 9. The generated signal is a CW signal that varies between 0 dBm and 40 dBm measured at the center frequency of the filter polarized by different bias voltages (0 V, 1.5 V, 3.8 V, and 10 V). The HB method simulations and measurement results are presented in Fig. 10.

In the literature, BST bulk ceramics nonlinear behavior has been hidden because of the high voltages used to tune. However, the BST component employed in this study requires voltages ranging from 0 V to 10 V, implying that small bias voltages will have an effect on intermodulation distortion (IMD).
In Fig. 10, the simulation and measurement results are presented. The simulated and measured threshold power levels are approximately 20 dBm and 30 dBm when the bias voltage is 0 V, respectively. For both simulation and measurement results, the IL compression drops 4 dB from the threshold power levels to the maximum input power level of 40 dBm. The simulation results lack accuracy between input power levels of 20 dBm and 35 dBm. This is due to the memory effects and losses that the nonlinear capacitor model used in this work does not contemplate. Alternatives are proposed further on in Section VI. Up to 1.5 V, the response of the filter indicates significant nonlinear distortion. By applying a bias voltage of 10 V, both simulation and measurement results reveal an IL that suffers no compression. In this case, the accuracy of the polynomial model is noticeable. These results demonstrate that the BST-based filter constitutes an alternative as a tunable device while simultaneously increasing its IL compression over $P_{in}$. Linearity is an essential metric in MW tunable filters. In this work, the results between the frequency bands covered from 0 V to 3.8 V indicate the linearity increase.

The one-tone characterization analysis outlines the broad applicability of BST technologies in RF front-ends. By applying 0 V bias to the designed filter, it can be used to control the dynamic range of the ADC. On the other hand, by applying a 1.5 V bias, it operates as a tunable filter up to 10 V with tunability of 100 MHZ, as shown in Fig. 8.
IV. SDR FRONT-END: DUAL-BAND APPROACH

A second-order Chebyshev dual-band BPF with central frequencies $f_0$ of 780 MHz and $f_0^II$ of 3.5 GHz, and fractional bandwidths $FBW^I$ of 10% and $FBW^II$ of 15%, respectively, is exemplified with 20 dB in-band return loss. The capacitance of the BST component ranges from 2 pF to 0.4 pF, changing the reactance slope ratio of the SIR to be implemented. As a consequence, similar to [29], it is deduced that the BST filter presents strong memory effects because lower and upper IMC can differ in power up to 5 dB [34]. These experimental results indicate that figures of merit like IP3 should be used with extreme care in applications that feature BST thin films. IP3 is only a valid linearity metric for static third-order systems operating in small-signal [32]. The BST filters measured in this work not only present higher order behaviors in small-signal but also large-signal memory effects. It is essential to measure IMD and evaluate IMR in the full power range that the BST filter operates to obtain a reliable picture of its nonlinear behavior.

The studies of the BST behavior according to the center frequency of the devices designed are explored in the next section. To design the 3D devices, it is selected a state-of-the-art implementation of a dual-band BPF, theoretically described in Section II. A range of tunable bands and a fixed (non-tunable) band are selected according to the SDR bands of interest. The major purpose is to demonstrate the ferroelectric component capabilities by displaying power limiting features and selectivity in a specified band of operation and input power excitation.

FIGURE 12. IMD measurements and IMR analysis of BST-based filter at 906 MHz (bias voltage of 0 V).

and 3.5 GHz can be calculated based on (6) as

\[
\frac{x^I}{x^II} = \frac{K_{12}^II}{K_{12}^I} = \frac{10\% \times 15.1}{15\% \times 4.9} = 4.5. \tag{10}
\]

The impedance and length ratio $R$ and $\alpha$ are 1.55 and 0.42, respectively, with a central frequency ratio of 4.48, a reactance slope ratio of 4.5, and an identical K inverter network as described in [29]. The electrical lengths of the $\lambda/4$ SIR are computed using (8), with the resulting $\theta_1$ and $\theta_2$ being 52.4° and 72.4°, respectively. The theoretically needed reactance slope $x^II$ at $f_0^II$ may be calculated simply from (6).

\[
x^II = \frac{K_{12}^II \sqrt{\frac{8}{118}}}{FBW^II} = \frac{4.9 \times \sqrt{1.4142} \times 1.4142}{15\%} = 47.14. \tag{11}
\]

Lastly, the impedances $Z_1$ and $Z_2$, shown in Fig. 6, are determined from (9) to be 30.4 $\Omega$ and 19.6 $\Omega$, respectively. The above computations yielded the dimensions $L_1$, $L_2$, $W_1$, and $W_2$ from Fig. 13 design. This filter was built with a Rogers 4350 laminate with a thickness of 0.762 mm and a dielectric constant of 3.66. In this scenario, two BST thin film components were also employed to examine both tunability and nonlinear properties in each band.

A. INSERTION LOSS AND TUNABILITY

In RF applications, the design of dual-band BPFs is of great interest. Tunability and power limiting capabilities are essential features that BST components may provide to these systems. The proposed dual-band BPF includes a fixed second band, while the BST component allows the first band to be adjustable for different filtering applications. To evaluate the tunability of the dual-band BPF, a bias voltage ranging from 0 V to 10 V was applied.

The return loss and IL of the dual-band BPF are displayed in Fig. 14a) and Fig. 14b), respectively. From Fig. 14c) and Fig. 14d), it can be observed that the measurement results match the simulated ones and that the first center frequency, $f_0^I$, is tunable in the range of 780 MHz to 1 GHz while the second center frequency, $f_0^II$, remains fixed. The IL varies over the tuning range from 1 dB to 0.6 dB, corresponding to the center frequency states ranging from 780 MHz to 1 GHz, respectively. It is also possible to conclude that the parasitic effects of the employed lumped elements do not produce
growing losses at higher frequencies. This impact can also be evident in the features of the return loss. The IL changes from 2 dB at 780 MHz to 1 dB at 1 GHz.

The key feature of this dual-band BPF is that it is tunable in the first band but fixed in the second band. This shows the many contributions a BST component can add to the RF design. The tuning properties are heavily influenced by the component in use.

B. ONE-TONE CHARACTERIZATION

The testing results of the performance factors, such as non-linear IL, threshold power level, and frequency selectivity on this device, are reported in the following section. The one-tone characterization was chosen to evidence the IL compression, as observed in the previous section.

The higher the input power, the larger attenuation the device provides as more energy is dissipated. The threshold power level can be obtained from the IL measurements. The simulation and measurement results for the filter first band, 780 MHz, are displayed in Fig. 15. The simulation results are based on the model described in Section II. By biasing the dual-band BPF to 0 V, it starts the IL compression at 15 dBm and achieves the minimum IL of 7.7 at 40 dBm. The measurement results reveal a threshold power level at 25 dBm and a decrease of the IL to 7.9 at 40 dBm. The measurement and simulation results when applying a 0 V bias are accurate, demonstrating the linearity of the BST thin films when higher input power is applied. The broadband IL is measured by sweeping the frequency of the input signal with different power levels. The memory effects induced by the ferroelectricity of the material introduced by charge carriers have a major influence on the observed nonlinear behavior of the device. As a result, a direct relationship between voltage control and IMD has been established. From the 2 V mark of bias voltage, the nonlinear behavior of the BST component disappeared in the first band. More importantly, the control of the second band is required to ensure that no IMD is produced by the component at any bias voltage. Such behavior is evident in Fig. 16, where the absence of IL compression demonstrates the linear nature of the component in the second band.

Single and dual-band BPFs are used in two separate applications described in the preceding sections. With these two examples, depending on the BST component selected, it may switch from highly nonlinear to linear in different frequency bands. Consequently, this research leads to the next section, which describes the frequency selectivity and power limiting properties required to manufacture 3fD devices.
V. THREE FUNCTIONAL DIMENSION DEVICE

The concept of 3fD devices emerged to mitigate interference and provide frequency selective surface capabilities for applications in new communication systems. These new passive devices will accommodate the signal depending on its operation, select the in and out-of-band signals (filter characteristic), change the frequency of operation via a DC bias voltage stimulus (variable filter characteristic), and accommodate the amplitude of signals, allowing to change the characteristics of the component based on its amplitude (clipping effect).

The measurements of the 3fD device were carried out using the one-tone measurement setup already described in the previous section, Fig. 9. A CW signal was swept both in frequency and power. The frequency was swept from 500 MHz to 4 GHz using 1 MHz steps, and the power sweep was performed in parallel from 0 dBm to 40 dBm.

In Fig. 17, the broadband IL is measured by sweeping the input signal frequency with different power levels ranging from 20 dBm to 40 dBm. The threshold power level may be obtained from the IL measurements according to the input powers. The higher the input power, the larger attenuation is provided by the device. In the range of the selected input power, the IL changes progressively from 1.04 dB to 7.79 dB. Furthermore, in Fig. 18, the same device is used to illustrate its highly linear behavior with high-power handling capabilities. The measurements proceeded as described previously, but the bias voltage of the BST components was fixed at 3 V. The increase in input power had no effect on the IL values. As a result, the device may be utilized as a purely tunable SDR front-end ranging from 0 to 40 dBm.

This dual-band SDR front-end exhibits nonlinear behavior based on the BST component bias voltage, which has an effect on the frequency tuning state. As a result, depending on the bias voltage, this device can tolerate the high output power levels of the power amplifier (PA) while also presenting or not an IL compression for the selected band. The dual-band BPF is polarized with two different bias voltages to demonstrate its capabilities. This device can be used in a variety of applications, including using a 0 V bias voltage in the BST component to reduce the effect of high-power jammers, or using a 3 V bias voltage to perform reconfigurable PA modules that can improve high-power handling capability and linearity with low filter losses.

VI. CONCLUSION

The 3fD device successfully protects RF receivers against jamming interference by rejecting signals that exceed a predetermined maximum power threshold while allowing weaker signals through and reinforcing the receivers dynamic range. The effects of voltage and frequency dependence on the nonlinearity of BST-based SDR front-ends have been analyzed. Increasing bias voltage reduces the power level of the generated third-order IMD when two-tone measurements are performed, as we can conclude from the single-band device analysis. The usage of the dual-band approach better understands the differentiated behavior regarding frequency.

This work fulfilled a crucial gap because the ferrite-based FSL solutions presented in state-of-the-art present very low power thresholds. The ferroelectric-based circuits proposed in this paper constitute a solution when high-power thresholds are required and, consequently, an innovative solution for high-power anti-jammers and dynamic range control.

Although the C-V behavior has been modeled for the component and its impact registered in the filter design, more studies of the nonlinear conductance are needed to predict the third-order intermodulation products regarding the bias voltage. Future work includes developing a model based on the Volterra series describing the frequency and nonlinear behavior of the BST thin films. New implementations with BST bulk and film ceramics constituted interesting studies to understand the nonlinear dependence regarding frequency and bias voltage.
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