A Voltage Controlled Oscillator Using Barium Strontium Titanate (BST) Thin Film Varactor

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Abstract— **Barium Strontium Titanate (BST) has a field-dependent permittivity and can be used as a dielectric in voltage tunable capacitors or varactors. These BST-based varactors are passive devices and have significantly different properties compared to semiconductor varactors. A voltage tunable oscillator using a BST thin film varactor was designed and characterized. The frequency of oscillation varied from 34.8MHz to 44.5 MHz (28% tuning) upon application of 7 volts tuning voltage. The VCO gain was 1.38MHz/V and the 2 nd harmonic was over 23dB below the fundamental throughout the tuning range.**

Index Terms— **Voltage controlled oscillator, varactors, ferroelectric films, harmonic distortion.**

I. INTRODUCTION

BST is a ferroelectric material that has a large electric-field dependent permittivity and simultaneously can have low dielectric loss. It has been used in the past to build voltage tunable capacitors used as tuning elements in tunable filters, phase shifters and delay lines [1]. The capacitance tuning mechanism in a BST varactor is in sharp contrast to that of a semiconductor varactor, the former being a spontaneous polarization effect whereas the latter is a variable space charge depletion effect. The characteristics of these two types of varactors can be expected to be different in terms of tuning voltage, tuning linearity, breakdown voltage and noise effects. The semiconductor varactor has been used extensively as a tuning element in voltage controlled oscillators (VCOs). This work uses BST-based varactors as a tuning element in a VCO and compares the characteristics of the VCO with that of a semiconductor varactor-based VCO.

VCOs are perhaps the most ubiquitous element in all communication systems, wired or wireless. In a wireless system the quality of the communication link is determined in large part by the characteristics of the VCO [2], [3]. A reversed bias semiconductor junction is typically used as the tuning capacitor in a VCO, wherein the applied voltage changes the depletion width and hence the tuning capacitance. The figure of merit of the VCO is primarily determined by the quality of the capacitor used and the RF voltage that can be applied across the capacitor [4]. The varactor must operate in the reversed bias region to avoid forward conduction and excess shot noise. Thus there is a limit to the RF voltage swing that can be impressed upon the capacitor and this imposes an inherent limitation on the lowest achievable phase noise in the VCO [5]**.** This is in sharp contrast to the BST varactor which can handle high RF voltage swings since there is no equivalent of a forward biased junction as in the case of a conventional semiconductor varactor. Now, the Q factor of a semiconductor varactor increases with increasing bias. Thus, while increased resonator Q is desirable, the increased RF voltage peak plus DC tuning voltage risks forward biasing the semiconductor junction. This is known as the junction bias effect and is minimized by using an array of back-to-back varactors. The BST varactor does not suffer this consequence.

Due to the fundamentally different tuning mechanism in the BST thin film varactor, a single BST varactor-based VCO will have markedly different spectral characteristics. In particular there is no limitation on the voltage swing; hence the spectral purity can be traded off with power consumption. It also has a symmetrical tuning curve and can be operated in either the bipolar or unipolar mode. Furthermore it is should have better noise characteristics than a semiconductor varactor, particularly in terms of lower $1/f$ noise and shot noise. Finally, the well-behaved capacitance-voltage curve of the BST varactor lends itself to lower K_{VCO} and therefore more robust Phase Locked Loop designs [6]. In this work the prospects of substitution of the semiconductor varactor with a BST thin film varactor for improving the overall spectral characteristics of a VCO is evaluated.

II. DESIGN AND FABRICATION

A 35−45 MHz range VCO was designed and characterized with both a semiconductor varactor and a BST varactor. The VCO was used as a test vehicle and the only element changed was the varactor so that any performance differences could be attributed to the devices themselves. The circuit diagram for the VCO is shown in Fig. 1.

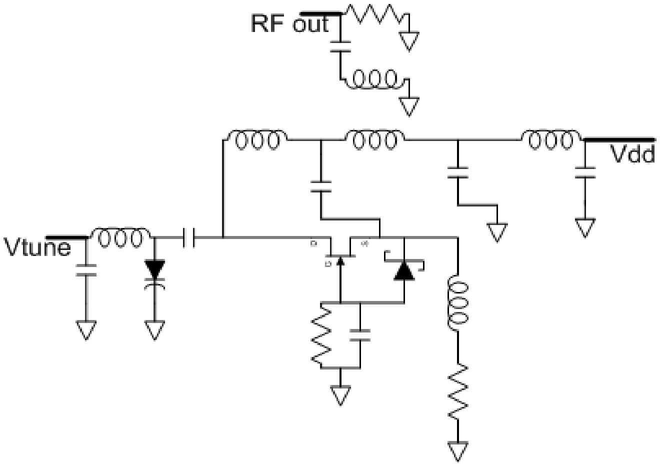

Fig 1: Circuit diagram of the VCO

The VCO resonator is designed to maximize the unloaded Q with tuning. When the resonator is embedded in a feedback loop of an active device the loaded Q is set to maximize Signal-to-Noise Ratio (SNR). A toroid inductor was selected to maximize the unloaded Q and maintain a convenient form for feedback adjustment. A tapped feedback Hartley oscillator configuration was used. A combination of components determines the resonator and VCO operating frequency. A Mathcad® routine enabled a minimum resonator inductance and varactor coupling capacitance to be determined. These component values are determined as a function of the varactor minimum capacitance, the varactor-tuning ratio, the desired VCO tuning range, and the total fixed parasitic resonator and active device capacitance. The varactor coupling capacitance and resultant unloaded Q associated with the BST or semiconductor varactor network is held constant to facilitate performance comparison. In the final VCO design the coupling capacitance to the varactor in the resonator tank was adjusted to either improve phase noise or adjust oscillator-tuning sensitivity. The semiconductor varactor[1] used had a nominal Q of 30 at 1-volt bias.

The BST varactor was fabricated using a metal organic chemical vapor deposition (MOCVD) process [7] achieving a nominal Q of 32 with no bias. The BST thin film was deposited on Si/SiO_2/Pt and had platinum (Pt) top electrodes which were patterned using the standard image reversal process. The MOCVD process provides excellent composition control, good area coverage and conformal coating and hence was used for fabrication of the BST thin film. Two BST capacitors were connected in series; this was done to obtain low value BST varactors since the thin film has very high permittivity (approx 300). The capacitors were diced from the wafer and attached to a 7-pin ceramic DIP carrier. The two top electrodes were then wire bonded to the gold pads. The zero-bias value of the BST varactor used in this work was found to be 200 pF and had a 3:1 tuning ratio from 1 to 12 volts bias. The core of the VCO used an n-Channel JFET (Model U 310 from Vishay Siliconix). The VCO was then assembled using discrete components on an FR4 board, see Fig. 2.

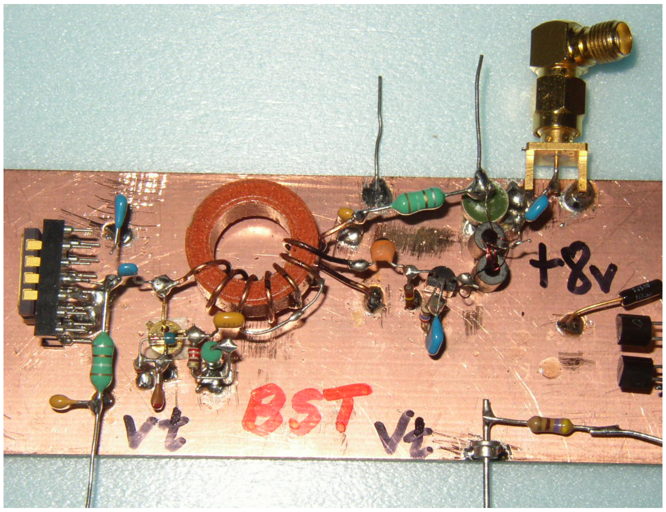

Fig 2: BST varactor VCO

III. MEASURED RESULTS AND DISCUSSION

The C-V curves of the BST and semiconductor varactors were measured on an analyzer at 10 MHz for bias voltages up to 9 volts. It can be seen from the C-V curves, Fig. 3, that the semiconductor varactor has greater non-linearity than the BST varactor. The VCO was tested using an Agilent E4445A PSA Series Spectrum Analyzer. The wideband spectrum and frequency tuning was measured at different tuning voltages. In Fig. 4 it can be seen that the BST varactor has a more linear tuning curve than does the semiconductor varactor and also has a lower VCO gain. This should allow a more robust PLL design compared to a semiconductor varactor VCO. The BST varactor VCO also has much better 2 nd harmonic performance compared to the semiconductor varactor. It can be seen in Fig. 5 that the 2 nd harmonic for the BST varactor VCO is well under −23 dBc over the entire tuning range where as the semiconductor varactor degrades to −18.0 dBc at high bias voltages. This is because the single varactor is subject to forward bias on peak value of the RF swing while the BST varactor is quite insensitive to it. The change in slope of the 2 nd harmonic curve for the BST varactor at different bias voltages can be attributed to the fact that over certain

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[1] Motorola MVAM115

regions of the C-V curve the BST is more non-linear than in other regions. Hence non-linearity, or conversely the approximation to a linear small signal model, is voltage dependent (see Fig. 3).

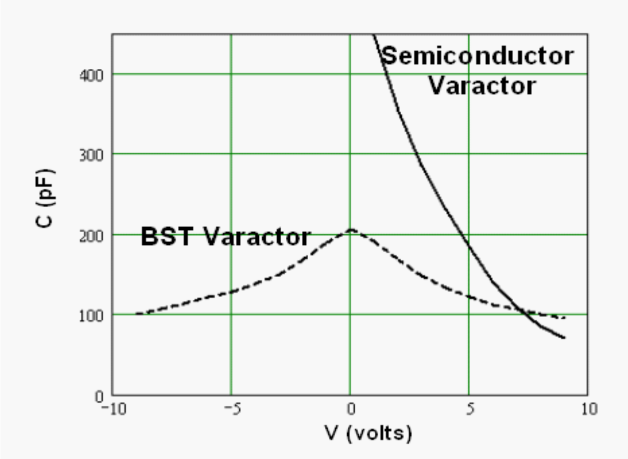

Fig 3: C-V curves for BST and semiconductor varactor

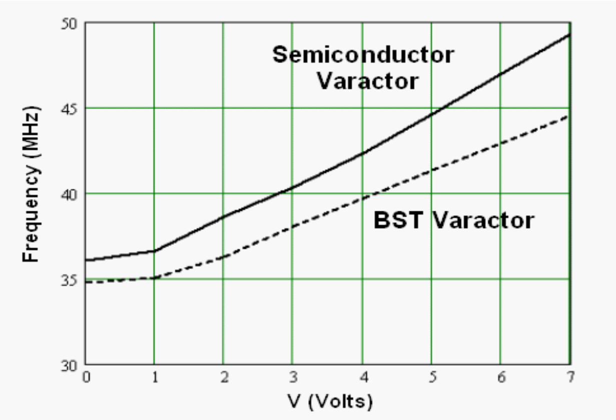

Fig 4: Tuning curves for BST and semiconductor varactor

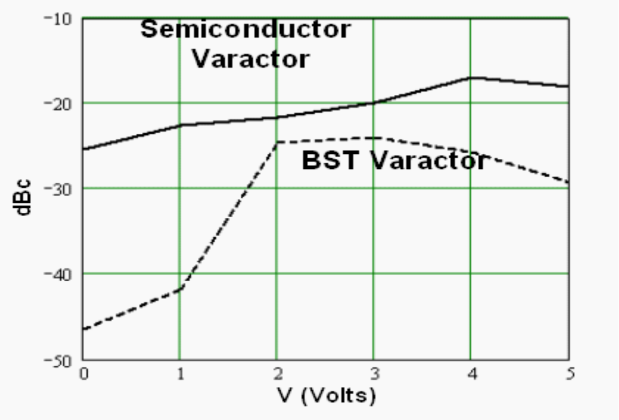

Fig 5: 2^{nd} Harmonic Vs Bias for BST and semiconductor varactor

The superior performance of the BST varactor is clearly shown in Fig. 6. It presents the broadband spectrum of the two VCOs at high bias voltages at one extreme of the frequency tuning range. This also corresponds to noise at one end of the voltage swing. This plot presents the broadband noise and it can be seen that the noise generated with the semiconductor varactor is much higher that that with the BST varactor.

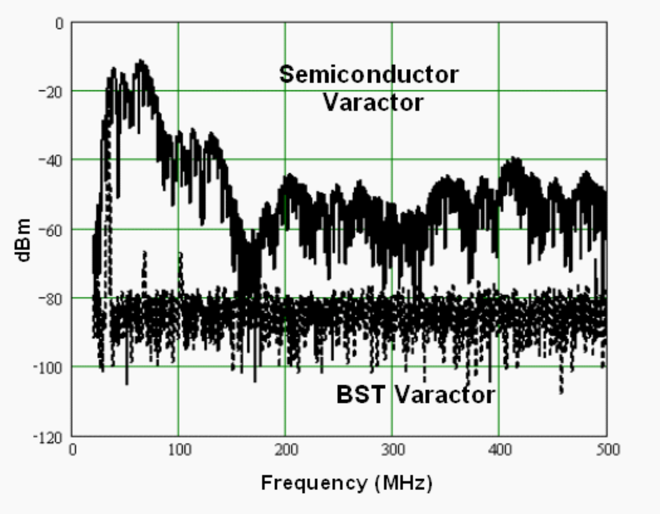

Fig 6: Wideband Spectra for the BST and semiconductor varactors at high bias voltage (6V).

With the semiconductor varactor, one extreme of the RF voltage swing results in mild forward conduction with shot noise generation. Thus the improvement in VCO spectral performance demonstrated in Fig. 6 can be attributed to the absence of varactor junction forward bias effect in BST varactors. Note that the Q of the BST varactor is 45, less than that of the semiconductor varactor which has a Q of 77. At increased bias voltages, the increase in varactor and resonator Q permits a higher peak RF resonator voltage. The semiconductor varactor tends to get slightly forward biased over the RF swing leading to a significant degradation in the spectrum where as the BST varactor does not suffer from such problems. This fact can be used advantageously for improving the phase noise of the oscillator by trading it with higher voltage swings across the tuning capacitor [8]. An improved phase noise can significantly decrease the BER, relax the specification on the power amplifier, and also address the problem of reciprocal mixing. Furthermore it also reduces the interference in adjacent channels [9], [10].

As discussed earlier, the favorable C-V curve of a BST varactor also allows greater suppression of the second harmonic and up conversion of noise from baseband. This is shown in Figs. 7 and 8. The wideband spectral plot is shown for 5 volts bias. It is seen that the BST varactor VCO has almost 11 dB more second harmonic rejection than the semiconductor varactor. This is very important in both transmit and receive chains and allows much greater receiver sensitivity than otherwise possible. This also mitigates the problem of the unwanted power located at the harmonics from falling into the desired channel upon mixing during the frequency conversion process [11]. In addition, the lower second order distortion reduces base-band-up-conversion effects and self-biasing.

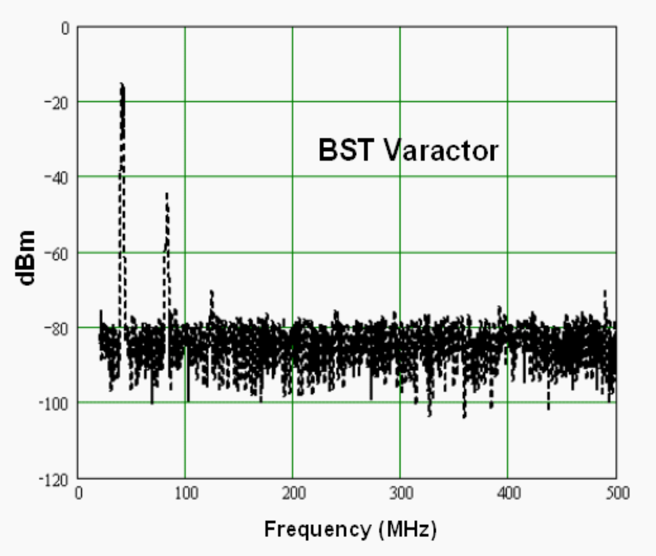

Fig 7: Wideband spectra for BST varactor VCO

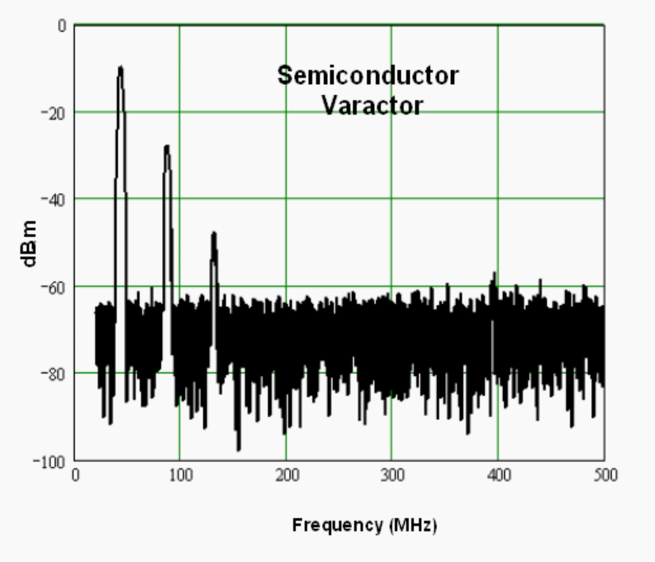

Fig 8: Wideband spectra for semiconductor varactor VCO

IV. CONCLUSION

A Voltage Controlled Oscillator (VCO) utilizing a BST thin film varactor was designed and characterized. The wideband spectral characteristics of the VCO are promising and harmonic rejection was significantly better than that for the VCO using a semiconductor varactor. Due to the absence of a semiconductor junction the BST VCO also tolerates higher RF swings and offers more design flexibility. The lower K_{vco} of the BST VCO renders the phase noise less sensitive to the noise and jitter injected or coupled from other circuitry. Thus it also lends itself to on-chip VCO designs. Overall the BST varactor based VCO seems to be a very strong candidate for high performance VCOs.

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