

Characterization of Nonlinear Behavior in A Tunable Phase Shifter Using Ferroelectric PZT Thin-Film Capacitors and Its Effect on System Performance

J.X. Qiu, D.C. Judy, J.S. Pulskamp, R.G. Polcawich, R. Kaul and F. Crowne

Army Research Laboratory, Adelphi, MD, 20783, USA

Abstract — In this paper, the nonlinear behavior in a tunable phase shifter using ferroelectric lead zirconate titanate (PZT) thin-film capacitors is described. The phase shifter is of reflection-type consisting of a coplanar waveguide Lange coupler and two ferroelectric PZT varactors on high resistivity silicon substrate. The nonlinearity is characterized by measuring the AM/AM and AM/PM transfer curves of the device, a technique that is commonly used to characterize power amplifiers. The responses of the device to two-tone and quadrature-amplitude-modulation waveforms are then estimated according to the measured transfer curves.

Index Terms — Ferroelectric thin-film, PZT, tunable phase shifter, nonlinear distortion, intermodulation, QAM, EVM.

I. INTRODUCTION

Successful deployment of phased-array systems requires the availability of a large quantity of low cost phase shifters with maximum phase agility and low insertion loss [1]. Phase shifters using ferroelectric barium strontium titanate (BST) have been investigated extensively for applications in phased-array antennas [2-4]. The phase adjustment is achieved by utilizing the DC electric field dependence of the dielectric constant. An alternative ferroelectric to BST, is lead zirconate titanate (PZT). PZT has not been extensively examined for microwave applications because its dielectric loss tangent is considerably larger than that of BST [5]. However, it has been demonstrated that it is possible to design PZT thin film tunable phase shifters with acceptable loss [6]. Furthermore, piezoelectrically actuated RF microelectromechanical system (MEMS) switches and digital phase shifters using PZT thin films have also been demonstrated using the same process [7,8]. This offers the possibility of a monolithically integrated circuits incorporating MEMS switches, MEMS digital phase shifters and continuously tunable phase shifters.

Digital communication systems use complex digital modulation techniques to increase spectral efficiency, to provide multiple access, and to improve reliability and anti-jamming capability. Complex modulation demands good linearity through the system. Power amplifiers are usually the main contributors to the overall system nonlinearity [9].

Because of the nonlinear nature of ferroelectric material, phase shifters based on ferroelectric materials such as BST and PZT exhibit nonlinear power dependence. The nonlinearity in BST phase-shifters has been investigated mostly using two-tone intermodulation distortion (IMD)

measurement [10]. However, for nonlinear amplifier characterization, a common practice is to measure its single-tone AM/AM and AM/PM transfer response. Assuming the amplifier is memoryless, time domain envelope analysis can be performed to predict its performance metrics for different input waveforms, such as IMD for two-tone, error vector magnitude (EVM) and adjacent channel power ratio (ACPR) for quadrature-amplitude-modulation (QAM) [11]. The AM/AM and AM/PM transfer response can also be used as a block model by itself or as the basis of a more complex, sophisticated model of the device with memory effect included for use in a system simulator [9].

In this paper, we will describe the measurement of the AM/AM and AM/PM response of a ferroelectric PZT phase shifter and its application for analyzing the nonlinear response of the phase shifter. The paper is organized as follows. In Section II, the design and fabrication of the PZT phase shifter are described. The small signal response of the phase shifter is presented in Section III. In Section IV, large signal characterization and measurement of the nonlinear AM-AM and AM-PM transfer curves are described. The application of nonlinear transfer curve for predicting the phase shifter performance for two-tone and QAM waveforms is presented in Section V.

II. DESCRIPTION OF THE PHASE SHIFTER

This device was fabricated using the standard ARL PiezoMEMS process at the Specialty Electronics Facility, US Army Research Laboratory, Adelphi, MD [7]. As shown in Figure 1, the phase shifter is of reflection-type consisting of a 3 dB hybrid with tunable PZT capacitors located on the through and coupled ports. The hybrid is a modified four-finger Lange coupler on high resistivity (greater than 10 k Ω .cm) silicon substrate. The CPW transmission line conductors consist of 7300 Å thick evaporated gold atop a 200Å thick adhesion layer of titanium. The air-bridges seen at the input, through, coupled, and isolated ports are used to tie the CPW grounds together as is typically done at all CPW transitions and discontinuities. The PZT capacitors are metal-insulator-metal (MIM) type, and consist of 1000Å of platinum, 5000Å of chemical solution deposited PZT (52/48), and 1000Å of platinum. The PZT MIM capacitor is 9 μ m in diameter with access to the bottom electrode provided by a

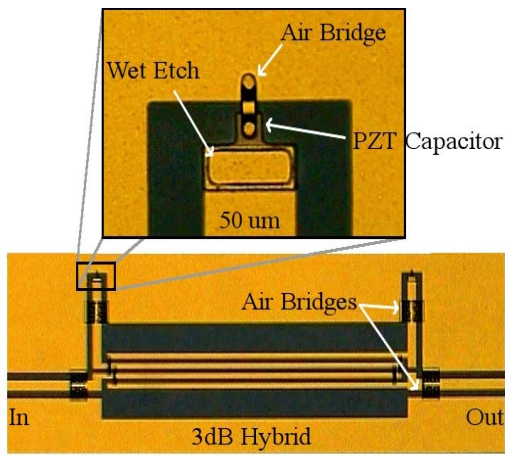


Fig. 1. The PZT Tunable Phase Shifter.

chemical wet etch to selectively remove the PZT. The top electrode is connected to the CPW ground by an air-bridge. The PZT components and the air-bridges are fabricated using the same process used to create the PZT based RF MEMS switch and digital phase shifters in Reference 7 and 8. The same DC bias for the tunable capacitors is provided through external bias tees at both the input and output ports, but future devices will include integrated on-chip bias tees.

III. SINGLE-TONE SMALL SIGNAL MEASUREMENT

All measurements were made on-wafer using ground-signal-ground air coplanar probes along with a vector network analyzer. Before the RF signal was applied to the device, the device was poled with +26V DC bias for approximately one minute. Fig. 2 shows the measured phase shift from 5-20 GHz for 0 to +26 Volt DC bias relative to the 0 volt case. Fig. 3 shows the measured insertion loss for the phase shifter with the same bias conditions as in Fig. 2. One port measurements of a single 9 μm PZT capacitors give an average loss of 1.2dB at 12GHz. The average loss of the PZT phase shifter is 2.3 dB at 12 GHz, and the maximum phase shift at 12GHz is 86° at +26V. These measurements give a figure of merit (FOM) of 37.4°/dB for the phase shifter and 109°/dB for the capacitors.

IV. SINGLE-TONE LARGE SIGNAL MEASUREMENT

For large signal measurement, the vector network analyzer was set to the power-scan mode at 12 GHz. To provide enough drive power, a 6-18GHz 100W microwave power module (MPM) was used as a booster amplifier. The MPM was driven at most only up to 6W to ensure good linearity. This was verified by landing the probes on a section of CPW transmission line on the wafer. The measured AM/AM and AM/PM transfer curves at 12 GHz are shown in Fig. 4 and 5. Before each measurement, the phase shifter was first poled with +26V DC bias for approximately one minute to ensure a well-defined starting state for the device and then biased at 0V. In this section, the discussion will be focused on the AM/PM curve due to the relatively low AM/AM values.

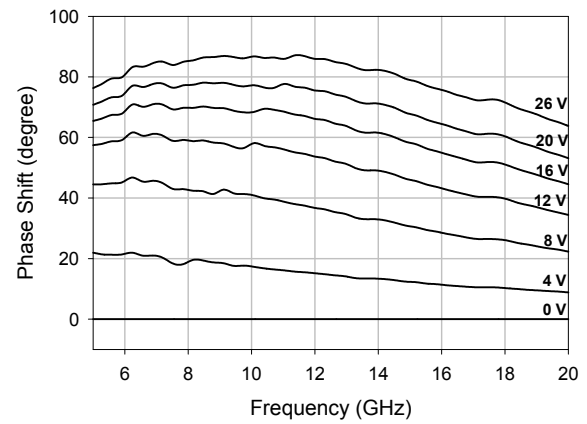


Fig. 2. Measured Relative Phase shift.

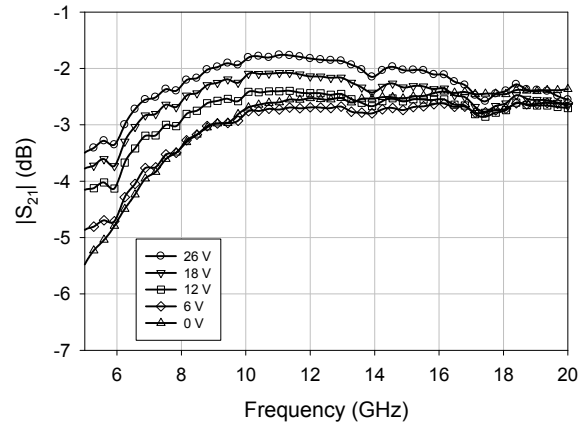


Fig. 3. Measured Insertion Loss.

There are two main contributions to the nonlinear power dependence in a ferroelectric capacitor. One is the nonlinear dependence of the dielectric constant on self electric field and the other is a thermal effect. For a paraelectric BST capacitor, because of its low loss tangent, its nonlinear characteristic is usually dominated by the self field effect and can be predicted from its small signal C-V characteristics [10]. The thermal effect only becomes important at high power level.

PZT has a relatively large loss tangent as compared to BST [5]. Consequently, the dielectric loss will cause the thermal effect to be more significant for PZT than for BST. For example, preliminary thermal analysis indicates that at $P_{in}=31\text{dBm}$, because of its small volume, the temperature of the PZT capacitor could be raised to higher than 300 °C, approaching the Curie temperature of PZT (52/48) (~375 °C). At $P_{in}=35\text{dBm}$, the temperature is expected to be well above the Curie temperature. This increase in temperature, according to the Curie-Weiss law, will increase the dielectric constant of the PZT film and results in a negative relative phase shift compared to the small signal response below the Curie temperature. Above the Curie temperature, further temperature increase will lower the dielectric constant and increase the relative phase shift. Fig. 5 appears to indicate that the thermal effect is the dominant contributing factor for the nonlinear power dependence in the current PZT capacitor geometry. However, a quantitative analysis must take into account the interaction between the thermal effect and the self

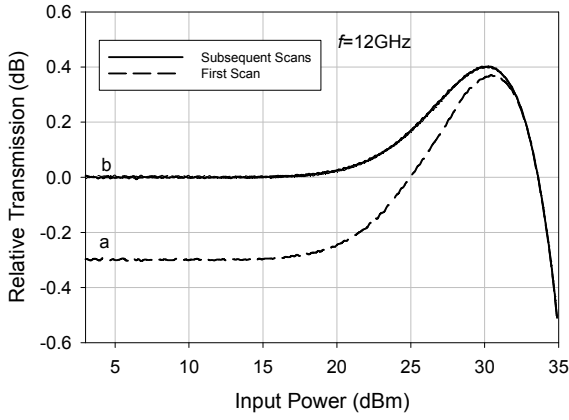


Fig. 4. AM/AM Transfer Curve.

field effect as well as the change in the loss tangent. The self electric field will lower the effective dielectric constant at a fixed temperature.

The thermal time constant of the capacitor is estimated to be about 0.16 μ s, which is much faster than the time to scan the power from 3 to 35 dBm (~ 10 s). The capacitors therefore reach thermal steady state virtually instantaneously. A thermal model of the PZT capacitor is currently being developed to better predict its temperature under dielectric loss heating.

A consequence of the dramatic increase in temperature is the evidence of de-poling as indicated by the change in the transfer curves between the first and subsequent RF power scans in Fig. 4 and 5. The high temperature experienced by the capacitors during the first power scan appears to de-pole the PZT ferroelectric completely and subsequent scans show no time dependence. This RF de-poling is further demonstrated in Fig. 6. In Fig. 6, for the 0V bias, both device 1 and 2 were DC poled at +26V and biased at 0V before RF power was applied. For the non-zero biases, the two devices were DC poled at +26V and then set to the corresponding biases (+4V for device 1 and -4V for device 2) before the RF power was applied. The fact that the final transfer curves for device 1 and 2 almost coincide with each other despite the opposite biases further suggests the occurrence of de-poling.

V. ANALYSIS OF MODULATED SIGNAL RESPONSE

If a modulated RF waveform is applied to the input of a completely de-poled phase shifter,

$$x(t) = A(t) \cos[2\pi f_c t + \theta(t)] \quad (1)$$

where f_c is the carrier frequency and $A(t)$ and $\theta(t)$ represent the amplitude and phase modulations, assuming the modulation time scale is much longer the thermal time constant of the PZT capacitors, the device is memoryless and the output waveform is then given by,

$$y(t) = g[A(t)] \cos\{2\pi f_c t + \theta(t) + \Phi[A(t)]\} \quad (2)$$

where $g(A)$ and $\Phi(A)$ are given by the “b” traces in Fig. 4 and 5. Eq. (2) can be used to estimate the distortion caused by the nonlinear transfer characteristics of the PZT phase shifter.

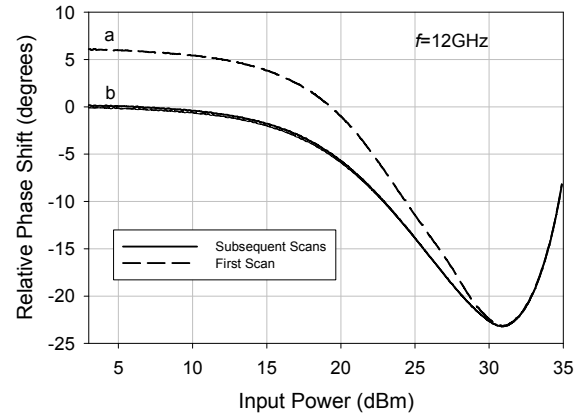


Fig. 5. AM/PM Transfer Curve.

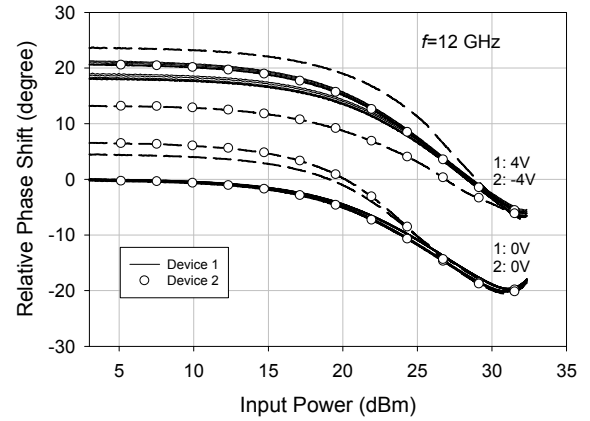


Fig. 6. AM/PM Transfer Curves with Opposite Biases. (Dash line: first scan. Solid lines: subsequent scans.)

A. Tone-Tone Waveform

When a waveform containing two carrier frequencies passes through the phase shifter, IMD products are produced at frequencies offset from the carriers by multiples of the frequency separation of the carriers due to nonlinearities. In Fig. 7, IMD products of difference orders are plotted as functions of average input power for the PZT phase shifter.

B. Digitally Modulated Waveform

The presence of nonlinearities has two effects on digitally modulated waveforms: (1) spectral regrowth caused by nonlinear distortion outside of the allocated bandwidth can create interference with neighboring signals; (2) waveform distortion can lower the receiver's ability to recover the transmitted information and increase the probability for information error.

To illustrate these two effects, the response of a phase shifter to a 32-QAM waveform was estimated. The 32-QAM waveform was filtered by a root-raised-cosine (RRC) filter with a roll-off factor of 0.5 before it was input in to the phase shifter. The output waveform was then filtered by another matched RRC prior to symbol recovery. In Fig. 8, the power spectral densities for two input power levels at the output of the phase shifter are shown. The spectral regrowth at high power level is clearly noticeable. In Fig. 9, the recovered

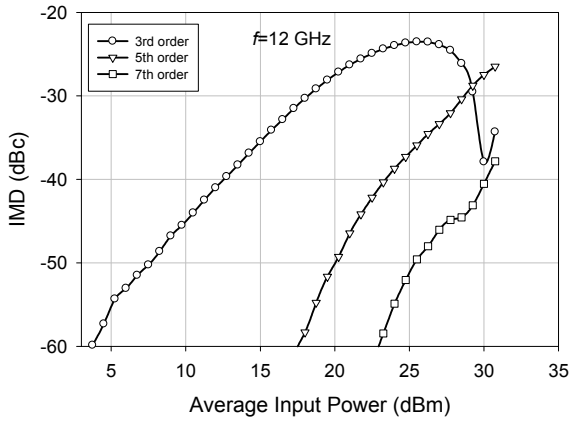


Fig. 7. IMD products vs. P_{in} .

constellation diagram for average $P_{in}=28.2$ dBm is shown. The PAPR of the 32-QAM waveform is about 6 dB, the peak power is therefore roughly 34.2 dBm. The presence of nonlinearity causes the recovered symbols to spread as well as deviate between the ideal constellations and the center-of-mass of the recovered symbols. Fig. 9 corresponds to an EVM of 3.1%. The acceptable levels of spectral regrowth, EVM and related metrics are determined by the overall system requirement.

VI. CONCLUSION

We have demonstrated the characterization of the nonlinear behavior in a ferroelectric PZT thin-film continuously tunable phase shifter by measuring its AM/AM and AM/PM nonlinear transfer curves. The responses of the phase shifter to modulated waveforms (two-tone and 32-QAM) are estimated using these nonlinear transfers curves. In order for ferroelectric phase shifters (both PZT and BST) to be used successfully in a real system, their nonlinearity must be analyzed not only as a single device but also in the context of their contribution to the overall system nonlinearity.

ACKNOWLEDGEMENT

The authors would like thank Mr. E. Viveiros and Mr. K. Kingeo for their assistance and support.

REFERENCES

- [1] J.C. Rock, J.H. Mullins, J.P. Booth and T. Hudson, "The Past, Present, and Future of Electronically-steerable Phased Arrays in Defence Applications," *Proc. IEEE Aerospace Conf.*, pp. 1-7, March 2008, Big Sky, Montana.
- [2] T. Ji, H. Yoon, J.K. Abraham and V.K. Varadan, "Ku-band Antenna Array Feed Distribution Network with Ferroelectric Phase Shifters on Silicon," *IEEE Trans. Microwave Theory & Tech.*, vol. 54, no. 3, pp. 1131-1138, March 2006.
- [3] L.-Y. V. Chen, R. Forse, A.H. Cardona, T.C. Watson and R. York, "Compact Analog Phase Shifters using Thin-Film (Ba,Sr)TiO₃ Varactors," *2007 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 667-670, June 2007

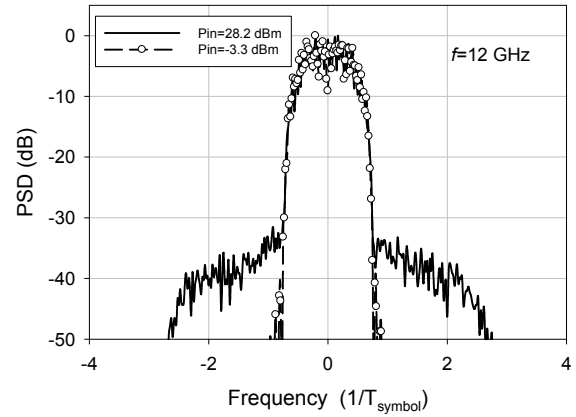


Fig. 8. Spectral Regrowth due to phase shifter nonlinearity.

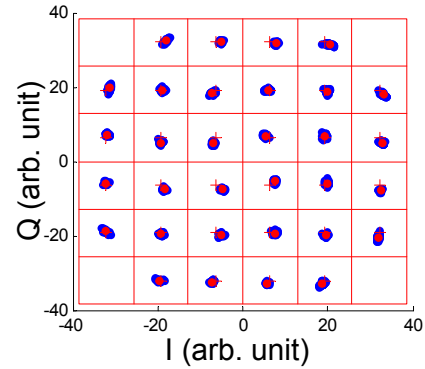


Fig. 9. Recovered Constellation Diagram.

- [4] D. Kim, Y. Choi, M.G. Allen, J.S. Kenney and D. Kiesling, "A Wide-band Reflection-type Phase Shifter at S-band Using BST Coated Substrate," *IEEE Trans. Microwave Theory & Tech.*, vol. 50, no. 12, pp. 2903-2909, December 2002.
- [5] A.K. Tagantsev, V.O. Sherman, K.F. Astafiev, J. Venkatesh and N. Setter, "Ferroelectric Materials for Microwave Tunable Applications," *J. Electroceramics*, vol. 11, no. 1-2, pp. 5-66, September 2003.
- [6] D.C. Judy, J.X. Qiu, J.S. Pulskamp, R.G. Polcawich and R. Kaul, "A Reflection-Type Continuously-Tunable Phase Shifter Using PZT Thin-Film Capacitor," Submitted to *Electronics Letters*.
- [7] R.G. Polcawich, J.S. Pulskamp, D. Judy, P. Ranade, S. Trolier-McKinstry and M. Dubey, "Surface Micromachined Microelectromechanical Ohmic Series Switch Using Thin-film Piezoelectric Actuators," *IEEE Trans. Microwave Theory & Tech.*, vol. 55, no. 12, pp. 2642-2654, December 2007.
- [8] R.G. Polcawich, D. Judy, J.S. Pulskamp, S. Trolier-McKinstry and M. Dubey, "Advances in Piezoelectrically Actuated RF MEMs Switches and Phase Shifters," *2007 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 2083-2086, June 2007
- [9] M.C. Jeruchim, P. Balaban and K.S. Shanmugan, *Simulation of Communication Systems, Second Edition*, New York: Kluwer Academic/Plenum Publishers, 2000.
- [10] A. Kozyrev, A. Ivanov, T. Samoilova, O. Soldatenkov and K. Astafiev, "Nonlinear Response and Power Handling Capability of Ferroelectric Ba_xSr_{1-x}TiO₃ film capacitors and Tunable Microwave Devices," *J. Appl. Phys.*, vol. 88, no. 9, pp. 5334-5342, November 2000.
- [11] S.C. Cripps, *Advance Techniques in RF Power Amplifier Design*, Boston: Artech House, 2002.