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13. ABSTRACT (Maximum 200 words)

This work has concentrated on developing thin-film tunable dielectric technology towards commercial viability for phase-shifters. Agile's varactor and phase shifter modeling has demonstrated the potential for this technology to provide low loss phase shifters utilizing Barium Strontium Titanate (BST) as the tunable dielectric material. Initial work involved fabrication of parallel plate capacitors as test structures which demonstrated the high quality of the BST films. Prototype phase-shifters utilizing such films were successfully demonstrated and issues such as intermodulation distortion (IMD) were explored and quantified in terms of design parameters. This technology was also compared with alternatives such as MEMS and GaAs MMICs. Specifically, the tradeoff between control voltage and performance variables such as IMD, power handling, and phase noise was explored and tabulated for the various approaches. Agile's varactors technology enables low-cost, low-loss phase shifters for DOD and commercial applications.

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FINAL PROGRESS REPORT ARO-BAA

Contract Title: *Thin-Film Phase Shifters*

Grant Number: DAAD19-00-C-0100

Performance Period: 1 August 2000 to 31 December 2001

Progress Summary:

This work has concentrated on developing thin-film tunable dielectric technology towards commercial viability for phase-shifters. Agile's varactor and phase shifter modeling has demonstrated the potential for this technology to provide low loss phase shifters utilizing Barium Strontium Titanate (BST) as the tunable dielectric material. Initial work involved fabrication of parallel plate capacitors as test structures which demonstrated the high quality of the BST films. Prototype phase-shifters utilizing such films were successfully demonstrated and issues such as intermodulation distortion (IMD) were explored and quantified in terms of design parameters. This technology was also compared with alternatives such as MEMS and GaAs MMICs. Specifically, the tradeoff between control voltage and performance variables such as IMD, power handling, and phase noise was explored and tabulated for the various approaches.

Task 1 : Optimizing loss of tunable dielectrics on low-cost substrate material

During the initial reporting period, Barium Strontium Titanate ($Ba_xSr_{(1-x)}TiO_3$, or BST) was identified as the tunable dielectric material which we believe to be the best near-term solution for commercially viable microwave varactor circuits. Two different Ba/Sr ratios with the same dopant concentrations were initially selected for investigation in sputtered thin-films. This material selection was based upon known behavior of these dopants in bulk Barium Titanate with respect to Curie point and oxygen complexes, properties which we believe will affect loss, tenability and long-term reliability. Sputtering was chosen because it is a proven thin-film deposition method in industry.

Appropriate substrates for material growth include quartz, borosilicate glass, silicon or sapphire. Quartz or glass substrates are attractive due to their low-cost and in the case of borosilicate glass the thermal match to silicon. However for Agile, integration issues with the current process dictated that sapphire be utilized in our initial efforts. Film growth for Agile was performed through a sub-contract with the University of California at Santa Barbara (UCSB) on a multiple-gun sputtering system. Utilizing a Platinum electrode stack Agile personnel fabricated parallel plate capacitors in order to investigate the capacitance-voltage and loss-voltage properties of our films. Films exhibiting high Q-factors in the GHz region were demonstrated. Figure 1 shows capacitance and Q-factor for various size RF devices at frequencies up to 10GHz for one of our films. Each curve represents a different capacitor size, with the Q-factor scaling inversely with capacitance in accordance with the device design.

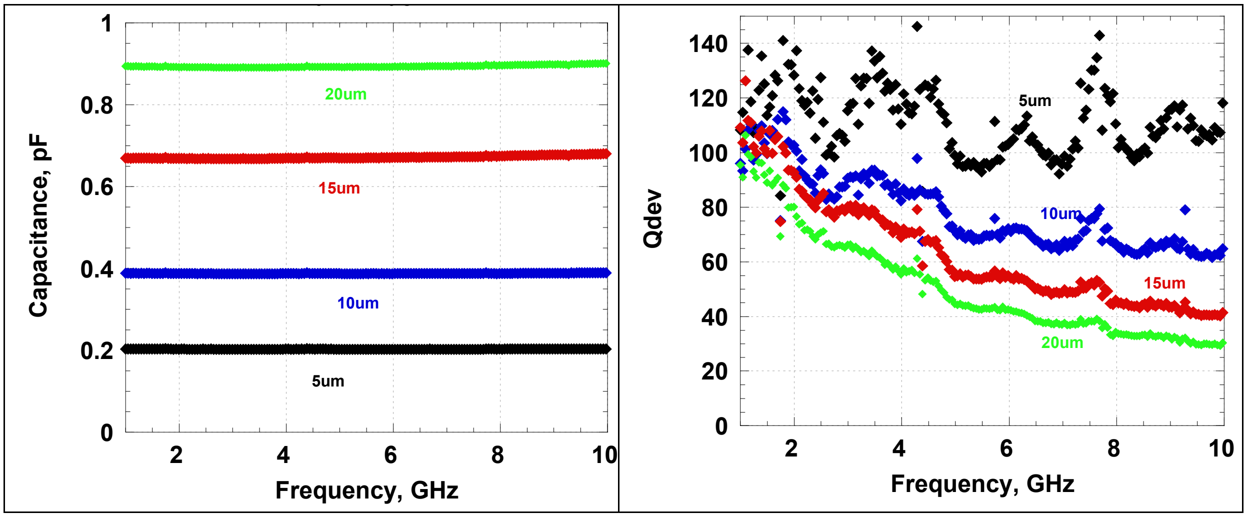

Figure 1: Example frequency dependence of capacitance and Q-factor for various sized RF devices fabricated by Agile

A reliability set-up was designed but not yet implemented under this program. Initial reliability studies on such devices, however, have indicated low-leakage which has been correlated to high-quality films.

Task 2: Thin-Film Phase Shifter Prototypes

Initial design of a distributed-circuit phase-shifter was done based on recent data out of UCSB on both high-Q STO capacitors and BST capacitors. Circuit optimization was studied though the generation of charts of phase shifter Figure of Merit and loss tangent versus tunability. Based on working RF device models, Agile continues to refine the design procedure for low-loss distributed-circuit phase shifters. The optimization procedure is done analytically using device and transmission-line loss models, and the designs are then verified for accuracy on a circuit simulator such as Agilent's Advanced Design System (ADS). Figure 2 shows the results of an optimization study for a 20GHz delay line on sapphire substrates. Designs were synthesized at the discrete points marked on the plot, with lines drawn between for clarity. Each point represents the lowest possible insertion loss for a given device technology (including transmission line losses). The device is specified by its overall Q-factor (including all loss mechanisms) and useable tunability. This figure demonstrates that improving the quality factor of the BST films will reduce insertion loss of the phase shifter.

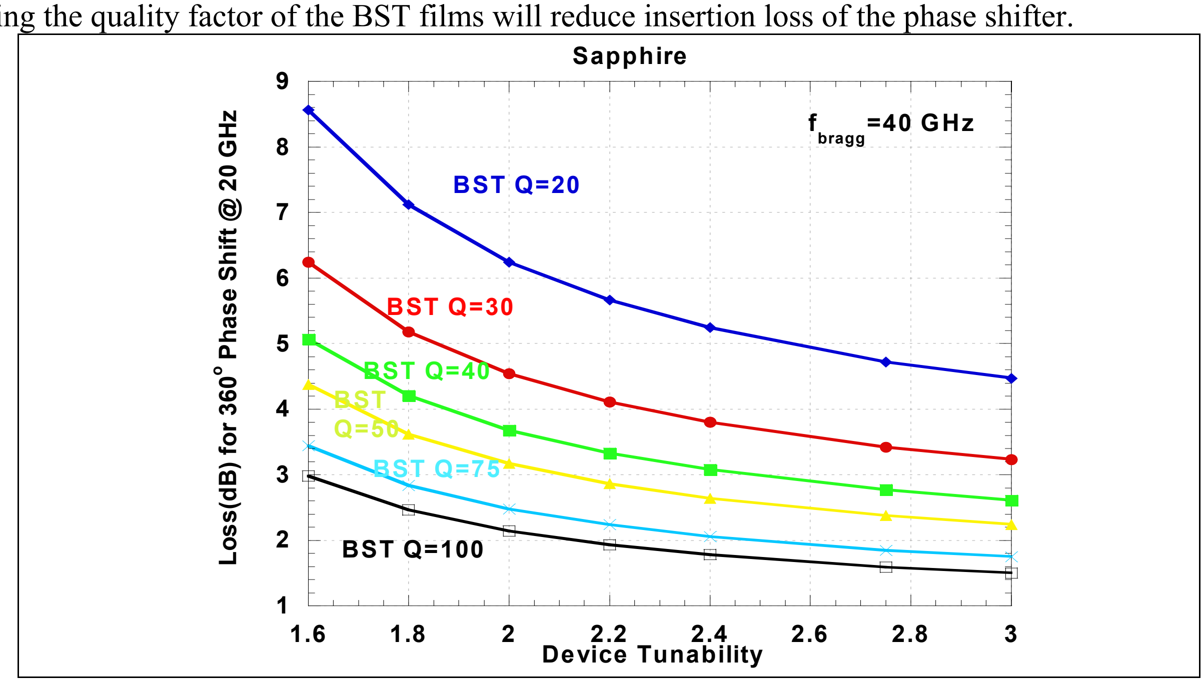

Figure 2: Optimum insertion loss for a 20GHz delay line for various device Q-factors and tunability

Prototype phase shifters were successfully demonstrated. Figure 3 shows measured differential phase shift from an initial distributed-circuit design (patent pending) which operated at 8GHz with a maximum insertion loss of <5dB.

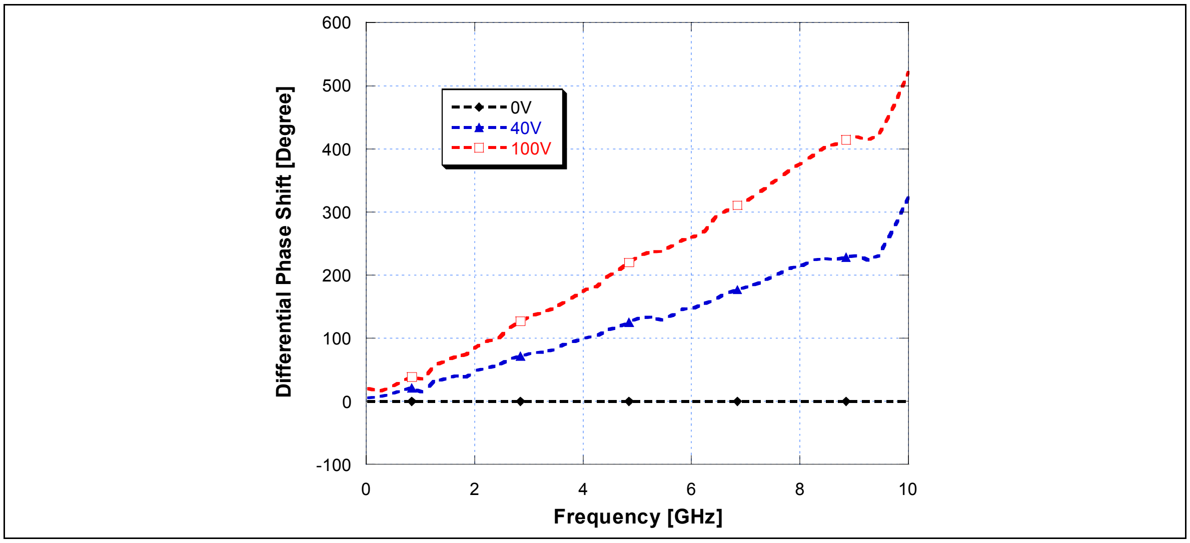

Figure 3: Measured differential phase shift at X-band (8GHz)

Under this contract we also completed study of intermodulation distortion (IMD) and third-order intercept point (IP3) on these structures. Using a coupled-mode analysis and the nonlinear wave equation, we found that the output power in the third-order product for a line length L is given by

$$P_3 = \left(\frac{1}{4}\chi Z_0 \beta_0 L\right)^2 P_{in}^3 \qquad (1)$$

where χ is a nonlinearity parameter, Z_0 is the characteristic impedance, β_0 is the propagation constant, and the power variables are in units of Watts. It is most convenient to work in dBm, in which case (1) becomes

$$P_3\ [\text{dBm}] = 20\log\left(\frac{1}{4}|\chi| Z_0 \beta_0 L\right) + 3P_{in}\ [\text{dBm}] - 60 \qquad (2)$$

The third-order intercept point, or IP3, (where $P_3 = P_{in}$) is therefore

$$IP3 = \frac{4}{|\chi| Z_0 \beta_0 L}\ [\text{W}] \quad \text{or} \quad IP3 = 30 - 10\log\left(\frac{1}{4}|\chi| Z_0 \beta_0 L\right)\ [\text{dBm}] \qquad (3)$$

This is a nice result, since it quantified IP3 directly in terms of design parameters. The nonlinearity parameter χ is the key parameter; although it is bias dependent, the maximum value usually occurs at zero bias, and is related to the device characteristics approximately as

$$\chi = \kappa \frac{\text{tunability}^2 - 1}{2V_{\max}^2} \qquad (4)$$

where κ is the loading factor (usually about 0.5), and $V_{\max}$ is the maximum allowable bias voltage. This result shows that devices with high breakdown voltages (thick films) will have the largest IP3. Hence, IP3 trades with control voltage. It should be mentioned that this result applies to lossless nonlinearity, and hence represents a worst-case IP3 since it assumes an ideal conversion efficiency for third-order products.

Task 3: Comparative Study of Thin-Film Phase Shifters and System Impact

Thin-film ferroelectric (TFF) technology has been compared to MEMS and GaAs MMIC devices for use in true-time-delay phase shifter structures of relevance to the Army phased-array needs. The following criteria have been explored:

Control Voltage: MMIC and thin-film ferroelectric (TFF) devices can be designed for low operating voltages (<20 V), whereas bulk ferroelectric (BF) may require >100 V, and the most reliable MEMS devices require large "pull-down" voltages of 50-75 Volts. This has important implications for many remote terminal or mobile applications. On the other hand, MMIC or TFF devices with low operating voltages may be susceptible to inter-modulation distortion (IMD) because of inherent device nonlinearities, whereas MEMS devices are not.

Power-Handling: In general, MMIC devices have limited power handling. Ferroelectric and MEMS devices can be designed for good power-handling, but there are tradeoffs and limitations. MEMS devices display membrane motion as a function of power level on the underlying transmission-line, which gives rise to a large-signal nonlinearity. The most important effect of this is the tendency to switch (snap down) at a critical value of transmission power. More rigid membranes can be constructed to increase power handling, but this trades-off with control voltage. TFF circuits can be made with thick films to increase power handling, but this also trades-off with control-voltage.

Tuning speed: MMIC and ferroelectric devices are capable of rapid tuning between phase states, whereas MEMS devices are inherently slow. The pull-down speed of MEMS devices can be made attractive through creative biasing schemes, but the pull-up speed is limited by the mechanical spring constant of the system. Exotic schemes have been devised to counter this problem, but none has yet proved viable.

Phase noise: MMIC and ferroelectric devices have intrinsically superior noise characteristics. Although not widely appreciated, MEMS devices are critically sensitive to mechanical vibration (so-called "microphonics"). When the device membrane vibrates, the capacitance changes which in turn modulates the transmission phase, leading to a severe source of phase-noise. MEMS devices can be improved in this respect by making the membranes more rigid, but this again impacts control voltages adversely.

Intermodulation Distortion: MEMs has no intrinsic nonlinearity which is capable of generating mixing products, and therefore is immune to IMD. MMIC and ferroelectric devices are inherently nonlinear and hence will suffer this problem to a certain extent. This can be controlled in ferroelectric devices more easily than in MMICs, but as mentioned above, the problem will likely involve a tradeoff between control voltage and desired IP3 level.

Packaging: MMICs are fragile and require hermetic packaging. MEMS devices will apparently require vacuum-sealed packages for reliable operation. Bulk ferroelectric (BF) devices may also require hermetic packaging if hydroscopic dopants such as MgO are used. In contrast, thin-film ferroelectrics (TFF) can be fully encapsulated during processing and hence are amenable to very simple and low-cost packaging technologies. We believe this may prove to be the most important and under appreciated cost-driver for advanced phase-shifter technologies. Even if MMIC and MEMS devices can be manufactured with lower unit costs, the packaging requirements will always make them more expensive than TFF devices.

With these comparisons, the following table has been constructed. It is interesting to note that no one technology stands out as superior on all counts. However we believe BST has the best long-term merit for low cost, low loss phase shifters. Key technical barriers to overcome appear to be RF loss, reliability (only initial tests have been performed under this contract), and lack of production infrastructure.

Table 1 – Comparison of GaAs, BST, and MEMS varactor technologies for distributed phase shifters

	GaAs	BST	MEMS
Tunability (at high Q)	High (2-5:1 typ)	Moderate (2-3:1 typ)	Low (<1.5:1)
RF Loss (Q)	Moderate (Q<60 typ.)	Moderate (Q<100 current)	Very Good (Q<200)
Control Voltage	<10V (unipolar)	<20 V (PP) >90 V (ID) (bipolar)	50-80 V (bipolar)
Tuning Speed	Fast	Fast	Slow
Power Handling	Poor	Trades with Control Voltage	Excellent
IMD	Poor	Trades with Control Voltage	Excellent
Packaging	Hermetic	Surface Mount (non-hermetic)	Hermetic
Cost Drivers	Lithography, Packaging	Lack of infrastructure	Packaging, lack of infrastructure
Projected Cost	Moderate to High	Low	Low to Moderate