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Distributed Phase Shifter with Pyrochlore Bismuth Zinc Niobate Thin Films

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***Abstract*—A monolithic Ku-band phase shifter employing voltage tunable $Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$ (BZN) thin film parallel plate capacitors is reported. BZN films were deposited by RF magnetron sputtering on single-crystal sapphire substrates. A nine-section distributed CPW loaded-line phase-shifter structure was designed. A differential phase shift of 175° was achieved with a maximum insertion loss of 3.5 dB at 15 GHz, giving a figure of merit ~ 50°/dB. To the best of our knowledge, this is the first demonstration of a monolithic tunable microwave circuit using BZN thin films.**

***Index Terms*—Phase shifters, coplanar waveguides, bismuth zinc niobate, thin films, tunable dielectric, non-ferroelectric**

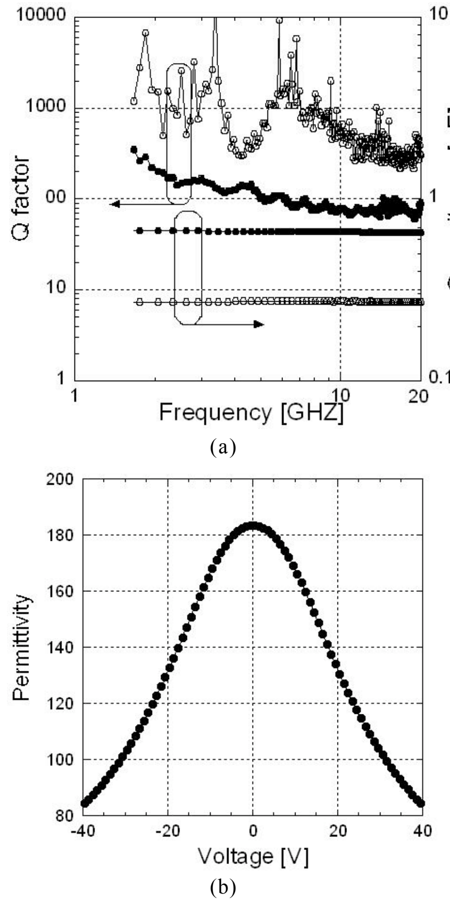
I. INTRODUCTION

ELECTRONICALLY-SCANNED antenna systems are attractive for many communication systems [1]. The cost of such systems is, however, often prohibitive, especially in commercial applications. Electronic phase-shifters also tend to suffer from high insertion loss, requiring additional levels of amplification that further drives up their cost. In recent years, new technologies such as microelectromechanical systems and electric field tunable dielectrics have been explored to implement low-cost and low-loss phase-shifters. Some compelling advances have been made in these areas [2]-[6]. This paper describes a phase-shifter implemented with a promising new tunable dielectric material, bismuth zinc-niobate ($Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$, or BZN).

Most of the literature on RF applications of tunable dielectrics has focused on the $Ba_xSr_{1-x}TiO_3$ (BST) thin films, and numerous device and circuit demonstrations have been reported [3]-[6]. Promising RF performance has been achieved [6]-[7], but in general the RF losses of BST-based devices are high.

In contrast to BST, BZN is a *non*-ferroelectric material with the cubic pyrochlore structure [8]. BZN exhibits a relatively large dielectric constant (150-200) and a low loss tangent (< 10^{-4} at 1 MHz) [10]. BZN thin films show a significant field-dependence of the permittivity [9], with more than 2:1 change in the dielectric constant at field strengths of ~ 2.4 MV/cm [10]. Although BZN bulk ceramics exhibit a dielectric relaxation and high losses at microwave frequencies [11], we have recently shown that dielectric losses of thin-film BZN capacitors remain low at least up to 20 GHz [12]. Hence BZN thin films are attractive for microwave tunable applications [10], [12]-[14].

Here, we present the first demonstration of a low-loss Ku-band phase shifter using BZN thin films. This circuit uses a distributed-circuit topology with coplanar waveguide (CPW) transmission-line periodically loaded with parallel-plate BZN capacitors.



(a)

(b)

Fig. 1. (a) Q factors and capacitances of BZN thin film (~ 320 nm) capacitors on sapphire substrates for 100 μm^2 (○) and 225 μm^2 (●) [12] (b) Tunability of BZN films (~ 160 nm) measured at 1 MHz [10].

II. DEVICE AND CIRCUIT DESIGN

For characterization at microwave frequencies, parallel plate or metal-insulator-metal (MIM) capacitors with Pt bottom

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electrodes were fabricated on sapphire substrates with capacitance values ranging between 0.1 and 2 pF. In contrast to planar (interdigital) capacitors, the parallel plate configuration allows for greater tunability at lower bias voltages, although this comes at the expense of increased fabrication complexity. The dielectric properties of BZN thin film capacitors were determined using a de-embedding procedure described in [12]. Figure 1(a) shows the frequency-dependent Q-factor and capacitance for two BZN capacitors at microwave frequencies [12]. Figure 2 shows a photograph and a schematic of the device in cross-section.

As can be seen in Fig. 1(a), the capacitance-frequency curves show very little dispersion, and the total device Q factor for the smallest devices is more than 200 at frequencies up to 20 GHz [12]. The size dependence of the device Q-factor is not currently understood, as it does not scale with geometry in a manner that is consistent with contributions from the series resistance of the metal electrodes or the loss tangent of the material. A similar size dependence was also observed in capacitors made from BST [16], and its origins remain an open question for research.

Figure 1(b) displays the electric field dependence of the BZN permittivity. The tunability of the large (30 µm x 50 µm) parallel plate device was 55%. Here the tunability was defined as $(\varepsilon_{max} - \varepsilon_{min})/\varepsilon_{max}$, where ε_{min} is the minimum measured permittivity at the maximum applied field, and is the dielectric constant at zero bias. The temperature dependence of the tunability of BZN is described in more detail in [14]. The surface roughness of the BZN films was about ~ 6 nm RMS (root mean square).

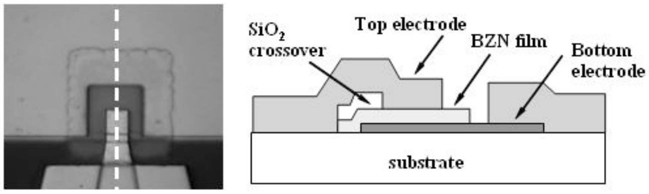


Fig. 2. Photograph of device and cross sectional schematic of the device

A distributed phase shifter was designed using principles described in [6], [15]. The structure is a periodically-loaded transmission-line that can be treated as a synthetic transmission line with a voltage-variable phase-velocity. The periodic nature of the loading introduces a cutoff frequency, often termed the Bragg frequency. The maximum differential phase-shift increases rapidly as the operating frequency approaches the Bragg frequency, as does the insertion loss. As described in [15], there is an optimum capacitive loading that minimizes the insertion loss for a desired total phase-shift. Discrete capacitive loading facilitates a precise control of the loading factor to achieve a good impedance match and optimal insertion loss.

A photograph and schematic of the phase shifter are shown in Fig. 3. The circuit represented here was designed for a ~ 270 degree differential phase-change at 15 GHz, assuming a 2:1 change in capacitance. The BZN was deposited on pre-patterned Pt bottom electrodes, as described in [12]. A BZN film thickness of ~ 150 nm yielded a capacitance density of ~ 10 fF/μm^2. The CPW center conductor width and gap are 30 and 70 µm respectively, giving an unloaded line impedance of ~70 Ω. Each unit cell in the phase shifter consists of two shunt-connected devices of ~ 0.125 pF, with a unit-cell length of 340 µm, yielding a Bragg frequency of ~ 25 GHz at zero bias.

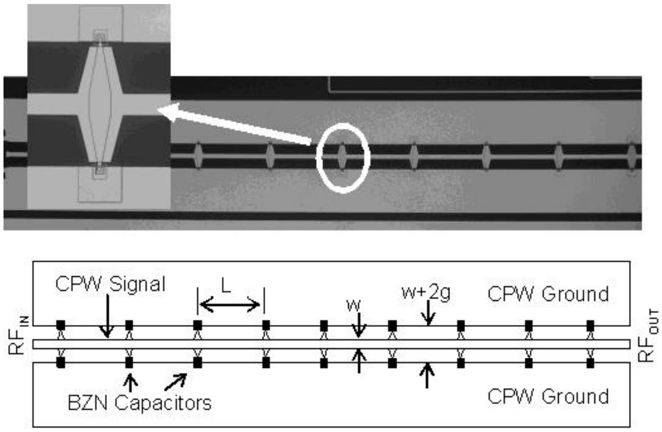
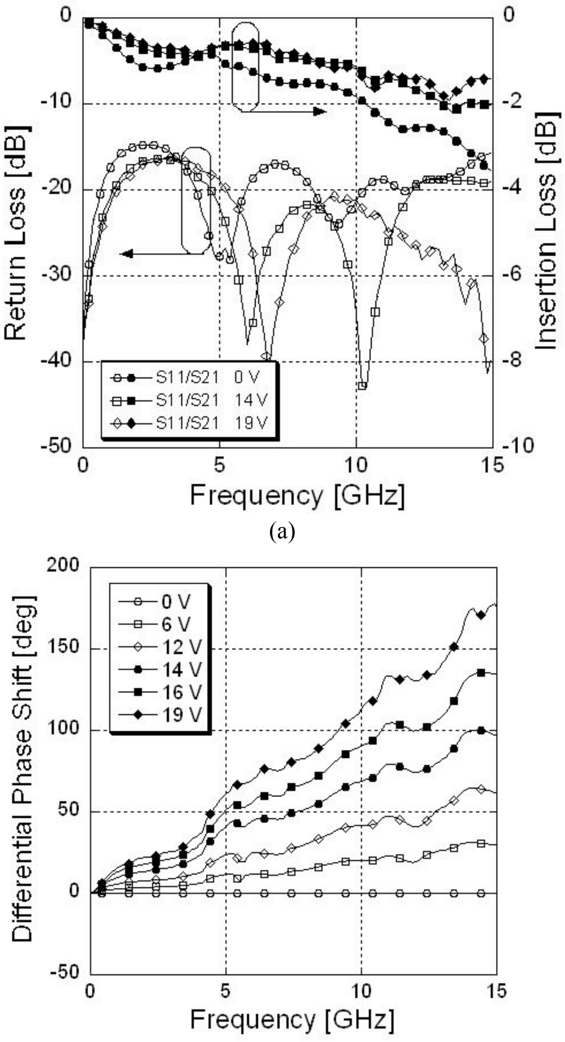


Fig. 3. Photograph and schematic of the BZN phase shifter (L: 340 µm, w: 30 µm, g: 70 µm)

III. MEASUREMENTS AND DISCUSSION

The two-port S-parameters of the phase shifter were measured using an Agilent Performance Network Analyzer 8362B. Figure 4 shows the insertion and return losses (a) and the differential phase shift (with respect to the zero-bias phase) as a function of frequency for several bias conditions (b). For frequencies well below the Bragg frequency, the phase shift increases linearly with frequency, and begins to deviate from a linear response as the Bragg frequency is approached. At the design frequency of 15 GHz, the highest insertion loss (at zero bias) is ~3.5 dB, and the maximum differential phase-shift is ~175° with an applied DC voltage between 0 and 19 V (applied through external bias tees to the center conductor), giving a 50 °/dB figure of merit at 15 GHz. The maximum differential phase-shift is less than the design value due to a premature breakdown of devices, which limited the range of DC control voltage that could be applied, and hence the total capacitance change that could be achieved.

Nevertheless, the total insertion loss is encouraging and significantly better than what was observed with BST-based phase shifters using a similar design (3 dB at 10 GHz for BST [5], [17], versus 1.8 dB at 10 GHz for BZN). Unlike BZN bulk or thick-film ceramics, BZN thin film devices maintain relatively low losses well into the microwave frequency region. The precise mechanisms of loss in these devices are still under investigation. The major limiting factor for the circuit figure-of-merit was the device tunability, which was limited by the voltage that could be applied before breakdown of the small devices. The breakdown voltages observed for the small RF devices were significantly lower than what was measured on larger area devices [12]. The reasons for the lower breakdown strengths of the small area devices will require further investigation.



(a)

(b)

Fig. 4. (a) Insertion and return losses (b) Differential phase shifts with applied DC bias of BZN phase shifter (BZN film thickness ~ 160 nm).

IV. CONCLUSION

An analog phase shifter using tunable cubic pyrochlore $Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$ thin films with MIM capacitors was designed and fabricated on a single-crystal sapphire substrate. This Ku-band phase shifter provided 0-175° phase shift with an insertion loss of 3.5 dB at 15 GHz at a maximum applied bias voltage of 19 V. The circuit performance could be improved by improving the breakdown strengths and utilizing metal bottom electrodes with higher conductivity than Pt. The results showed that BZN thin films represent a promising alternative tunable dielectric for low loss RF/Microwave tunable applications.

REFERENCES

[1] S. K. Koul and B. Bhat, *Microwave and Millimeter Wave Phase Shifters Vol.1., Dielectric and Ferrite Phase Shifters*, Artech House Inc., 1991.

[2] S. Barker and G. M. Rebeiz, "Distributed MEMS True-Time Delay Phase Shifters and Wide-Band Switches," *IEEE Trans. on Microwave Theory Tech.,* vol. 46, No.11, pp. 1881, Sept. 1998.

[3] J. Nath, D. Ghosh, J. Maria, A. I. Kingon, W. Fathebab, F. Franzon, and M. B. Steer, "An Electronically Tunable Microstrip Bandpass Filter Using Thin-Film Barium-Strontium-Titanate (BST) Varactors," *IEEE Trans. on Microwave Theory Tech.,* vol. 53, No. 9, pp. 2707, Sept. 2005.

[4] D. Kim, Y. Choi, M. G. Allen, J. S. Kenney, and D. A. Kiesling, "Wide-Band Reflection-Type Phase Shifter at S-band using BST Coated Substrate," *IEEE Trans. on Microwave Theory Tech.,* vol. 50, No. 12, pp. 2903, Dec. 2002.

[5] E. Erker, A. S. Nagra, Y. Liu, P. Periaswamy, T. R. Taylor, J. Speck, and R. A. York, "Monolithic Ka-Band Phase Shifter using Voltage Tunable $BaSrTiO_3$ Parallel Plate Capacitors," *IEEE Microwave Guided Wave Lett.*, vol. 10, No. 1, pp. 10, Jan. 2000.

[6] B. Acikel, Y. Liu, A. S. Nagra, T. R. Taylor, P. J. Hansen, J. S. Speck, and R. A. York, "A New Performance Phase Shifters using $Ba_xSr_{1-x}TiO_3$ thin films," *IEEE Microwave Guided Wave Lett.*, vol. 12, No. 7, pp. 237, July. 2002.

[7] A. Vorobiev, P. Rundqvist, K. Khamchane, and S. Gevorgian, "Silicon Substrate Integrated High Q-Factor Parallel-Plate Ferroelectric Varactors for Microwave/Millimeterwave Applications," *Appl. Phys. Lett.* **83**, 3144 (2003).

[8] I. Levin, T. G. Amos, J. C. Nino, T. A. Vanderah, C. A. Randall, and M. T. Lanagan, "Structural Study of an Unusual Cubic Pyrochlore $Bi_{1.5}Zn_{0.92}Nb_{1.5}O_{6.92}$," *J. Solid State Chem.* **168**, 69-75 (2002).

[9] W. Ren, S. Trolier-McKinstry, C. A. Randall, and T. R. Shrout, "Bismuth Zinc Niobate Pyrochlore Dielectric Thin Films for Capacitive Applications," *J. Appl. Phys.* **89**, 767-774 (2001).

[10] J. W. Lu, and S. Stemmer, "Low-Loss, Tunable Bismuth Zinc Niobate Films Deposited by RF Magnetron Sputtering," *Appl. Phys. Lett.* **83**, 2411 (2003).

[11] J. C. Nino, M. T. Lanagan, and C. A. Randall, "Dielectric Relaxation in Bi_2O_3-ZnO-Nb_2O_5 Cubic Pyrochlore", *J. Appl. Phys.* **89**, 4512-4516 (2001).

[12] J. Park, J. W. Lu, S. Stemmer, and R. A. York, "Microwave Dielectric Properties of Tunable Capacitors Employing Bismuth Zinc Niobate Thin Films," *J. Appl. Phys.* **97**, 084110 (2005).

[13] J. Park, J. W. Lu, S. Stemmer, and R. A. York, "Microwave Planar Capacitors Employing Low Loss, High-K, and Tunable BZN Thin Films," presented at the *IEEE MTT-S International Microwave Symposium,* Long Beach, CA, June 2005.

[14] A. K. Tagantsev, J. W. Lu, and S. Stemmer, "The Temperature Dependence of the Dielectric Tunability of Pyrochlore Bismuth Zinc Niobate Thin Films," *Appl. Phys. Lett.* **86**, 032901 (2005).

[15] A. S. Nagra and R. A. York, "Distributed Analog Phase Shifters with Low Insertion Loss," *IEEE Trans. on Microwave Theory Tech.,* vol. 47, No. 9, pp.1705, Sept. 1999.

[16] B. Acikel, Ph.D. Thesis, University of California Santa Barbara, 2002.

[17] B. Acikel, Y. Liu, A. S. Nagra, T. R. Taylor, P. J. Hansen, J. S. Speck, and R. A. York, "Phase Shifters using (Ba,Sr)TiO_3 Thin Films on Sapphire and Glass Substrate," *IEEE MTT-S International Microwave Symposium Digest*, pp. 1191, 2001.