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A Thin Film Distributed Phase Shifter Based on Pyrochlore, Bismuth, and Zinc Niobate

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ABSTRACT

There is news of a monolithic Ku-band phase shifter that uses capacitors made of voltage-tunable Bi1.5Zn1.0Nb1.5O7 (BZN) thin films. On single-crystal sapphire substrates, BZN films were deposited using RF magnetron sputtering. A phase-shifter structure with nine sections was constructed using dispersed CPW loading lines. At 15 GHz, a figure of merit of about 50°/dB was obtained, resulting in a differential phase shift of 175° and a maximum insertion loss of 3.5 dB. So far as we are aware, this is the first instance of a BZN thin film-based monolithic adjustable microwave circuit.

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

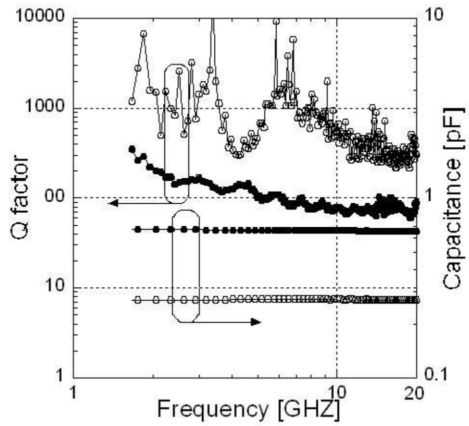
I.INTRODUCTION

Many communication systems find electronically-scanned antenna systems desirable [1]. However, such systems may be rather expensive, particularly for commercial use. The substantial insertion loss typical of electronic phase-shifters necessitates extra amplification stages, which in turn increases their price. The development of low-cost, low-loss phase-shifters has recently prompted research into novel technologies including electric field adjustable dielectrics and microelectromechanical systems. Significant progress has been achieved in several domains [2]– [6]. In this article, a phase-shifter that makes use of bismuth zinc-niobate (BZN), an intriguing novel tunable dielectric material, is detailed.

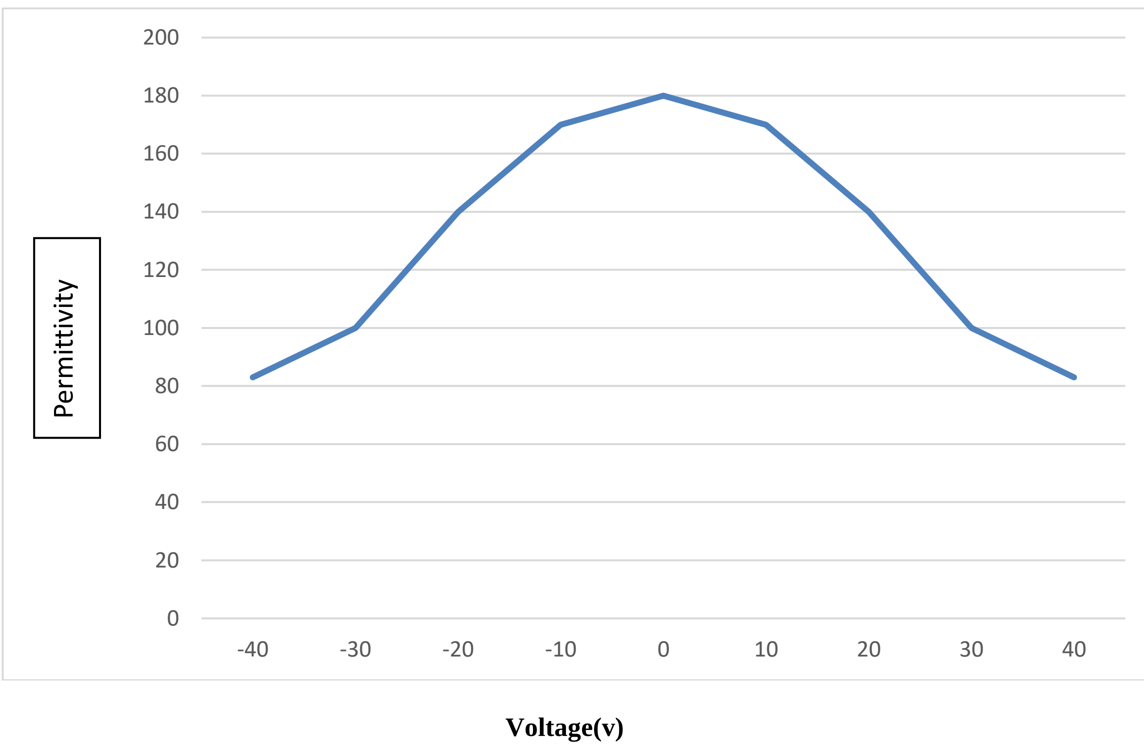
Numerous device and circuit demonstrations have been published, with the majority of the literature focusing on BaxSr1-xTiO3 (BST) thin films and their RF applications [3]-[6]. There has been some promising RF performance [6]-[7], although BST-based devices often have large RF losses.

A non-ferroelectric material with a cubic pyrochlore structure, BZN differs from BST in this regard [8]. The dielectric constant of BZN is rather substantial, ranging from 150 to 200, and its loss tangent is minimal, measuring less than 10-4 at 1 MHz [10]. The permittivity of BZN thin films is significantly field-dependent [9], and at field strengths of around 2.4 MV/cm, the dielectric constant changes by more than 2:1 [10]. Despite the fact that BZN bulk ceramics dielectric relax and have significant losses at microwave frequencies [11], our recent work has shown that thin-film BZN capacitors maintain minimal dielectric losses up to 20 GHz [12]. Therefore, BZN thin films have a lot of potential for uses that include microwave tuning [10], [12]–[14].

The first proof of concept for a Ku-band phase shifter with minimal loss, implemented using BZN thin films, is shown here. Periodically filled using parallel-plate BZN capacitors, this circuit employs a distributed-circuit architecture with a coplanar waveguide (CPW) transmission line.



(a)



(b)

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

II. DEVICE AND CIRCUIT DESIGN

Microwave characterization was carried out using sapphire substrates that had capacitance values ranging from 0.1 to 2 pF, in the form of parallel plate or metal-insulator-metal (MIM) capacitors with Pt bottom electrodes. The parallel plate structure offers more tunability at lower bias voltages than planar (interdigital) capacitors, but also increases manufacturing complexity. A de-embedding approach was used to estimate the dielectric characteristics of BZN thin film capacitors [12]. The capacitance and frequency-dependent Q-factor of two BZN capacitors operating at microwave frequencies are shown in Figure 1(a) [12]. Figure 2 displays a cross-sectional view of the device along with a schematic and an image.

At frequencies up to 20 GHz, the overall device Q factor for the smallest devices exceeds 200, and there is very little dispersion in the capacitance-frequency curves (Fig. 1(a)) [12]. At this time, we do not know how the device Q-factor grows with shape; this is because it does not scale in a way that is compatible with contributions from the metal electrodes' series resistance or the material's loss tangent. The source of this size dependency is still a mystery, however it was also seen in BST capacitors [16].

The dependency of the BZN permittivity on the electric field is seen in Figure 1(b). The huge parallel plate device, measuring 30 µm x 50 µm, has a tunability of 55%. In this case, the tuneability Figure 3 shows a picture and a schematic of the phase shifter. The circuit shown here was intended for a phase-shift of around 270 degrees at 15 GHz, supposing a capacitance change of 2:1. Following the method outlined in [12], the BZN was applied to Pt bottom electrodes that had already been designed. The capacitance density was around 10 fF/□m2 when the BZN coating was approximately 150 nm thick. With a width of 30 µm and a gap of 70 µm, the CPW center conductor has an unloaded line impedance of around 70 □. With a unit-cell length of 340 µm and two shunt-connected devices of about 0.125 pF, the phase shifter's unit cells produce a Bragg frequency of around 25 GHz when subjected to zero bias.
the dielectric constant when there is no bias, and the observed permittivity at the highest applied field. For a more in-depth description of how the tunability of BZN depends on temperature, see [14]. The root mean square (RMS) surface roughness of the BZN films was around 6 nanometers.

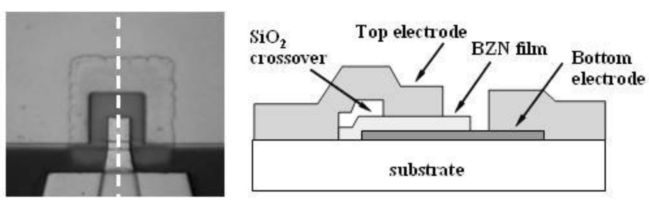


Fig. 2. Photograph of device and cross sectional schematic of the device

Based on the ideas presented in [6], [15], a distributed phase shifter was created. You may think of the structure as a synthetic transmission line with a voltage-variable phase-velocity; it's a periodically-loaded transmission line. The Bragg frequency—a cutoff frequency—is introduced by the periodic loading. Both the insertion loss and the maximum differential phase-shift grow exponentially as the operating frequency gets closer to the Bragg frequency. For each given total phase-shift, there exists an ideal capacitive loading that reduces insertion loss to a minimum, as detailed in [15]. To get an ideal impedance match and insertion loss, discrete capacitive loading allows for fine-grained adjustment of the loading factor.

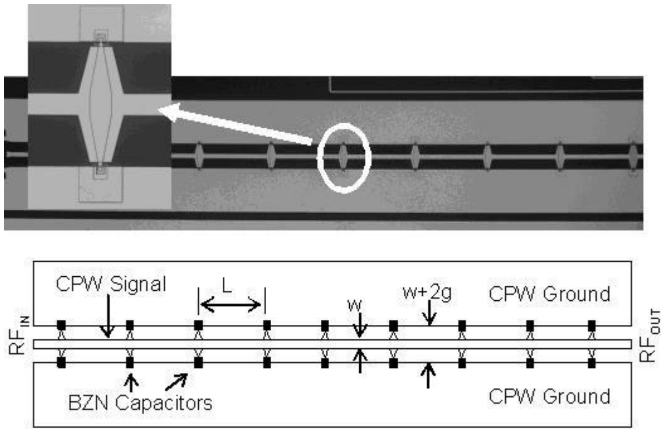
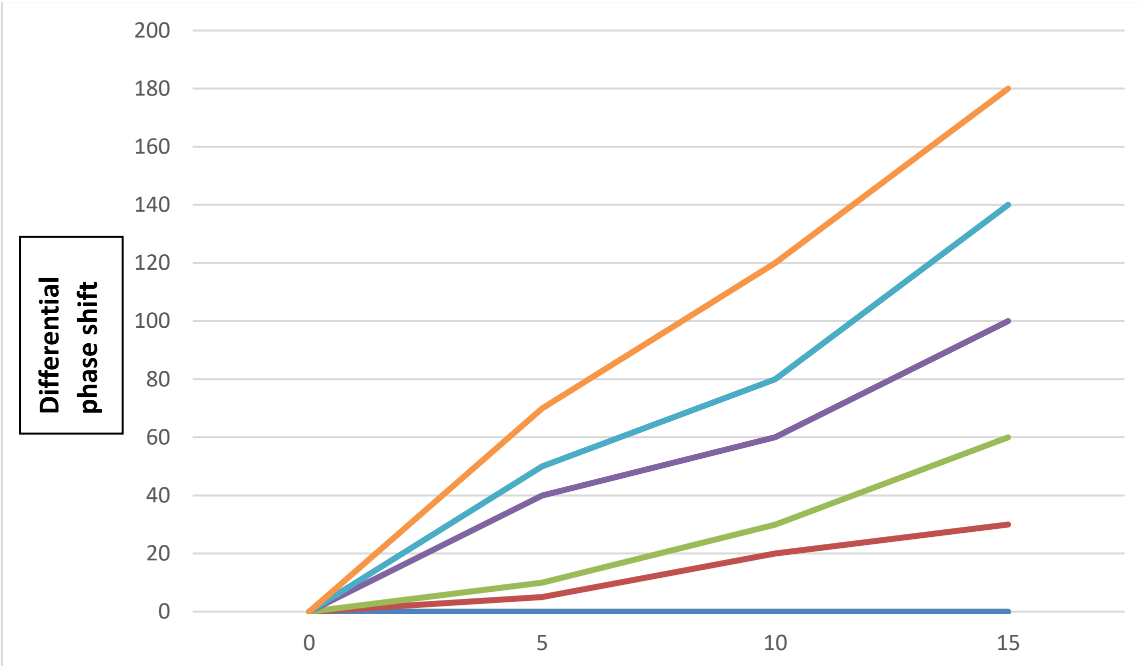


Fig. 3. Photograph and schematic of the BZN phase shifter (L: 340 µm, w: 30 µm, g: 70 µm)

III. MEASUREMENTS AND DISCUSSION

An Agilent Performance Network Analyzer 8362B was used to test the phase shifter's two-port S-parameters. Diagram 4 displays, for various bias settings (b), the frequency-dependent insertion and return losses (a) and the differential phase shift (with regard to the zero-bias phase). When the frequency is far lower than the Bragg frequency, the phase shift grows in a linear fashion; however, when the Bragg frequency is approached, the phase shift starts to behave differently. The greatest insertion loss at 15 GHz, measured at zero bias, is around 3.5 dB, while the largest differential phase-shift is about 175° when a DC voltage between 0 and 19 V is given to the center conductor using external bias tees, resulting in a figure of merit of 50 °/dB at 15 GHz. The devices failed before their expected lifespan was up, limiting the DC control voltage range and, by extension, the total capacitance change that could be accomplished, resulting in a lower maximum differential phase-shift than the intended value.

Even so, the overall insertion loss is promising and much better than what was seen with phase shifters based on BST that used a comparable design (3 dB at 10 GHz for BST [5], [17], compared to 1.8 dB for BZN). Thin film BZN devices, in contrast to thick film or bulk BZN ceramics, keep losses minimal even while operating in the microwave frequency range. Researchers have not yet determined the exact loss processes in these gadgets. The circuit figure-of-merit was severely constrained by the device tunability, which was in turn constrained by the voltage that could be applied before the little devices broke down. Comparing the breakdown voltages of small and big area RF devices revealed that the former had far lower values [12]. Investigation into the causes of the small area devices' lower breakdown strengths is warranted.



Frequency (GHz)

Fig. 4. Insertion and return losses

IV. CONCLUSION

The design and fabrication of an analog phase shifter on a single-crystal sapphire substrate included the use of tunable cubic pyrochlore Bi1.5Zn1.0Nb1.5O7 thin films with MIM capacitors. At 15 GHz and a maximum bias voltage of 19 V, this Ku-band phase shifter offered a 0-175o phase shift with an insertion loss of 3.5 dB. Using metal bottom electrodes with greater conductivity than Pt and increasing the breakdown strengths might enhance the circuit performance. Findings indicate that BZN thin films could be a good substitute tunable dielectric for low loss RF/microwave tunable uses.

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