2.4 GHz Continuously Variable Ferroelectric Phase Shifters Using All-Pass Networks

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***Abstract*—Continuously variable ferroelectric (BST on sapphire) phase shifters based on all-pass networks are presented. An all-pass network phase shifter consists of only lumped LC elements, and thus the total size of the phase shifter is kept to less than 2.2 $mm \times$ 2.6 mm at 2.4 GHz. The tunability (C_{max}/C_{min}) of a BST interdigital capacitor is over 2.9 with a bias voltage of 140 V. The phase shifter provides more than 121° phase shift with the maximum insertion loss of 1.8 dB and the worst case return loss of 12.5 dB from 2.4 GHz to 2.5 GHz. By cascading two identical phase shifters, more than 255° phase shift is obtained with the maximum insertion loss of 3.75 dB. The loss figure-of-merit of both the single- and double-section phase shifters is over 65°/dB from 2.4 GHz to 2.5 GHz.**

***Index Terms*—All-pass network, ferroelectrics, interdigital capacitor, phase shifter.**

I. Introduction

PHASED-ARRAY antennas often require continuously variable and fast tuning phase shifters to optimally control main beam and null directions. For commercial applications, such as an 802.11b wireless local area network (WLAN), small-size and low-cost phase shifters are necessary to realize a beamforming network for applying spatial filtering to separate carrier signals from interference [1]. One of the promising technologies to realize such a phase shifter employs $Ba_xSr_{1-x}TiO_3$ (BST) thin films. Several design options for BST phase shifters have been proposed in the past [2]–[6]. Reflection-type phase shifters consist of a 3-dB coupler and reflective loads [2], [3]. While wide bandwidths may be achieved with the reflection type topology, the coupler contributes directly to the insertion loss of the phase shifter, and requires a large portion of the die area. Loaded-line phase shifters are controlled by varying the capacitive loading on a coplanar waveguide transmission line [5], [6]. One drawback of this topology is that long lines are required to achieve the necessary phase-shift range at low frequencies.

Another approach to reduce the size of a phase shifter is adopting an all-pass network. Adler *et al.* [7] proposed a digitally switched phase shifter using all-pass networks.

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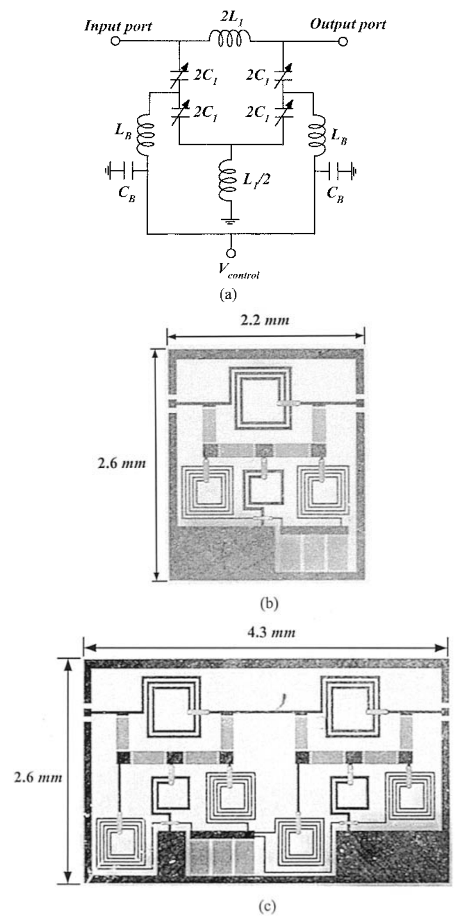

Fig. 1. All-pass network phase shifters. (a) Schematic. (b) Photomicrograph of a single-section phase shifter. (c) Photomicrograph of a double-section phase shifter.

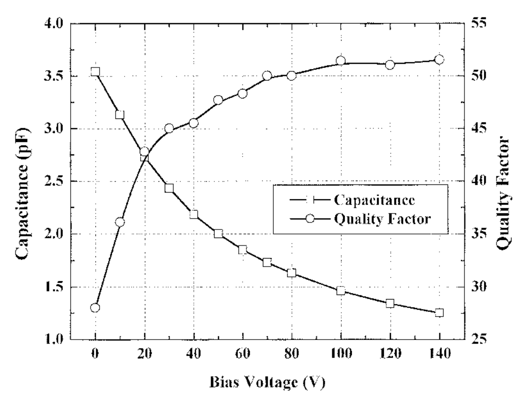

Fig. 2. Measured capacitances and quality factors of a BST interdigital capacitor with 13 fingers at 2.4 GHz.

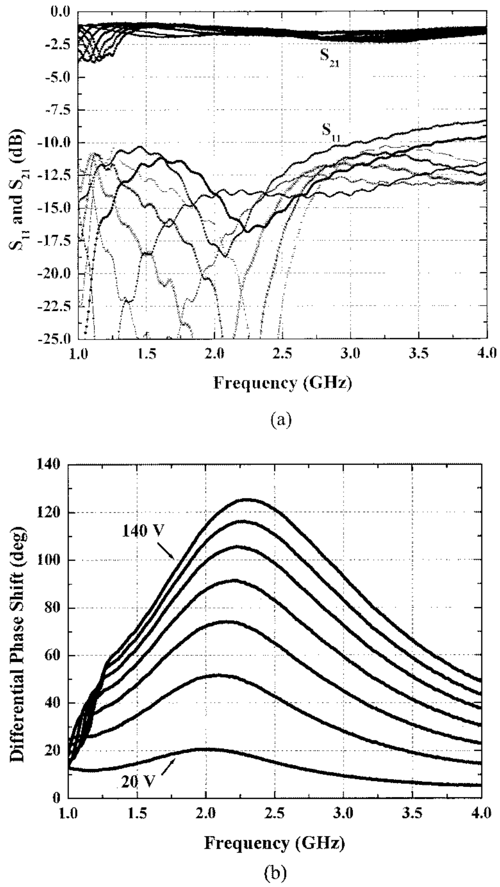

Fig. 3. Single-section phase shifter. (a) Measured insertion and return loss. (b) Differential phase shift with respect to the phase at 0 V.

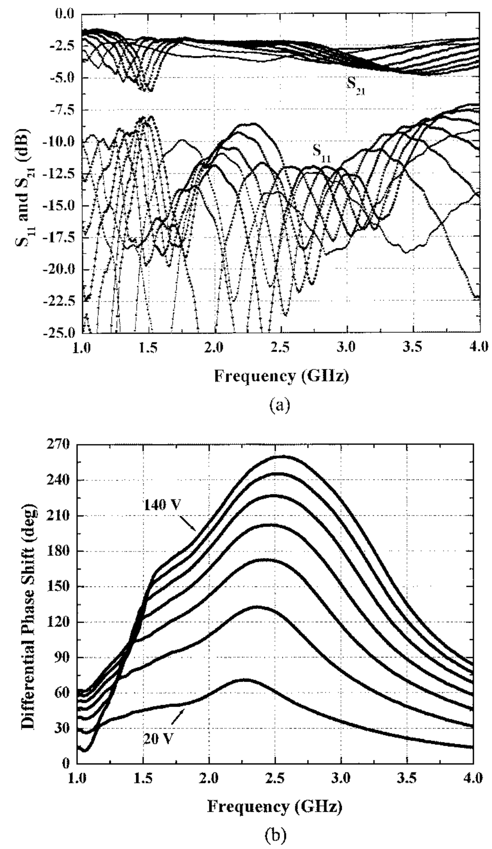

Fig. 4. Double-section phase shifter. (a) Measured insertion and return loss. (b) Differential phase shift with respect to the phase at 0 V.

A continuously variable phase shifter based on an all-pass network was fabricated using a GaAs MESFET process by Hayashi *et al.* [8]. The phase shifter, which was comprised of two quarter-wave-length transmission lines with series resonant circuits, demonstrated good performance with a compact dimension at Ku-band. Also, an all-pass network phase shifter using tuning capacitors and inductors with MESFET varactors was presented along with a buffer amplifier from 7 to 8.5 GHz [9].

In this paper, we propose all-pass network phase shifters based on BST coated sapphire substrates at 2.4 GHz. The phase shifter consists of only LC lumped elements, and thus the total size is very compact. By cascading two identical phase shifters, a larger phase-shift range can be obtained with the same control voltage.

II. Phase-Shifter Design

Details of the phase-shifter fabrication process were first presented in [3]. To summarize, the substrate was prepared by depositing BST on an r-plane sapphire substrate using open-atmosphere CCVD process [10]. The BST and sapphire thicknesses were 0.45 μm and 675 μm, respectively. The first metal layer was formed by evaporating 300 Å/22 000 Å/2500 Å, respectively, of Cr/Cu/Au.

The proposed phase shifter is derived from an all-pass network, which consists of two spiral inductors, four BST capacitors and a bias network as shown in Fig. 1(a). The capacitors are the main control elements of the phase shifter and they are series connected on each branch in order to apply a bias voltage only to capacitors. Interdigital capacitors are chosen over parallel plate capacitors in order to maintain a planar process that requires no metal layers beneath a BST thin film. The spacing between fingers is 4 μm. Two inductors, of which the ratio is four, are inserted between the input and output ports, and at the connection point of capacitors. The reflection coefficient S_{11} and transmission coefficient S_{21} can be expressed using even-odd mode analysis. If both L_1 and C_1 are changed at the same rate, the matching condition is preserved so that the reflection coefficient S_{11} should be zero. Tunable inductors may be created by equivalent series or parallel LC networks with with BST capacitors. However, this will result in higher loss. Therefore, in this design, only capacitance is allowed to change. The maximum and minimum resonant frequencies can be expressed as follows:

$$\omega_{0\min} = \frac{1}{\sqrt{L_1 C_{1\max}}} \quad (1)$$

$$\omega_{0\max} = \frac{1}{\sqrt{L_1 C_{1\min}}} \quad (2)$$

where, C_{1max} is the maximum value of the capacitor C_1 at 0 V, and C_{1min} is the minimum value at the highest bias voltage. The maximum and minimum resonant frequencies are optimized to enable a good tradeoff between phase-shift range and loss from 2.4 GHz to 2.5 GHz with a tunability of 3. The photomicrographs of the fabricated single-section and double-section phase

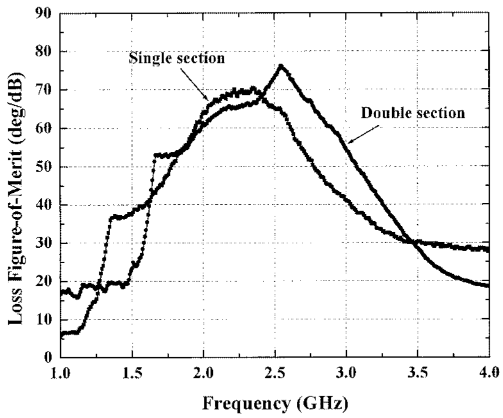

Fig. 5. Loss figure-of-merit of the phase shifter as a function of frequency.

shifters are shown in Fig. 1(b) and Fig. 1(c). The total size of the phase shifter is 2.2 $mm \times$ 2.6 mm for a single section and 4.3 $mm \times$ 2.6 mm for a double section.

III. Experimental Results

All measurements were made on an HP8753C Vector Network Analyzer with Cascade Microtech coplanar probes. One- or two-port S-parameters of the capacitors, inductors and phase shifters were measured from 1 GHz to 4 GHz with a bias voltage range of 0–140 V. Measured capacitances and quality factors as a function of bias voltage are shown in Fig. 2. Capacitances and quality factors at 2.4 GHz were extracted using the open and short devices [11], resulting in 3.5 pF at 0 V and 1.25 pF at 140 V. This implies that the tunability of the capacitor, which can be defined as C(0 V)/C(140 V), is 2.9. Also, the minimum quality factor of the capacitor is 28 at 0 V and is increasing as a bias voltage increases. Such a high quality factor is the main advantage over a parallel plate structure along with simple fabrication process. Further reducing the spacing between fingers can decrease a control voltage for the same tunability. The measured inductance and quality factor of $2L_1$ are 11.5 nH and 13, respectively, whereas the values of $L_1/2$ are 2.6 nH and 20, respectively, at 2.4 GHz.

Fig. 3 shows the insertion loss, return loss, and differential phase shift with respect to the phase at 0 V for the single-section phase shifter. The phase shifter provides more than 121° phase shift over a 140 V bias with the maximum insertion loss of 1.8 dB and the return loss of better than 12.5 dB from 2.4 GHz to 2.5 GHz. The insertion-loss variation over all bias states is below 0.5 dB in the same frequency range. Even though the differential phase shift is strongly dependent on a frequency, the phase variation from 2.4 GHz to 2.5 GHz is below 4° for all bias states, as shown in Fig. 3(b).

The measured results for the double-section phase shifter are shown in Fig. 4. The insertion loss varies from 2.2 dB to 3.75 dB depending on a bias voltage from 2.4 to 2.5 GHz. The return loss is higher than 9.5 dB for all bias states. The measured phase shift is continuous from 0° to 255° at 2.4 GHz and the phase variation from 2.4 to 2.5 GHz is below 5° for all bias states. With the exception of insertion-loss variation, it is seen that the cascade of two sections scales directly from the single-section phase shifter. Fig. 5 shows the loss figure-of-merit of the phase shifter, which is calculated as the ratio of the differential phase shift and the maximum insertion loss. The single-section phase shifter provides more than $65°/\mathrm{dB}$ from 2.4 GHz to 2.5 GHz. The double-section phase shifter also shows more than $68°/\mathrm{dB}$ from 2.4 GHz to 2.5 GHz. Out of band, the phase shifter shows around $76°/\mathrm{dB}$ at 2.55 GHz.

IV. Conclusion

Continuously variable phase shifters fabricated on BST coated sapphire substrates are presented in this letter. Using all-pass networks, the phase shifter provides more than 121° phase shift with the maximum insertion loss of 1.8 dB from 2.4 GHz to 2.5 GHz. The double-section phase shifter is also fabricated by cascading two identical single-section phase shifters, resulting in more than $68°/\mathrm{dB}$ from 2.4 GHz to 2.5 GHz, and $76°/\mathrm{dB}$ at 2.55 GHz. These phase shifters have been realized by only LC lumped elements, so that the total size of the phase shifters is very compact. The authors believe this to be the best performance and the smallest size obtained to date for an S-band ferroelectric phase shifter.

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