Performance of a K-Band Voltage-Controlled Lange Coupler Using a Ferroelectric Tunable Microstrip Configuration

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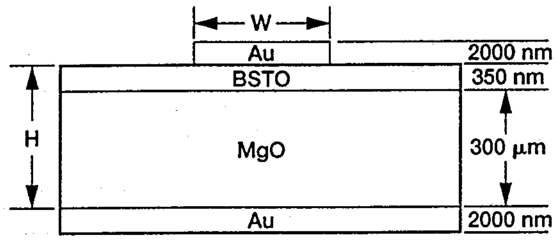
***Abstract*—We report for the first time on the performance of a Au/$Ba_{0.6}Sr_{0.4}TiO_3$ (BSTO)/MgO two-layered microstrip voltage-controlled Lange coupler (VCLC) designed for Ku- and K-band frequencies at room temperature. Tight coupling of 3 dB or higher was obtained over a frequency range of 14–19 GHz. At K-band frequencies, the coupling was voltage-controllable using the nonlinear dc electric field dependence of the relative dielectric constant of BSTO ($\varepsilon_{r\mathrm{BSTO}}$). The coupling level was improved from −11.6 to −3.7 dB at 20 GHz with an applied dc electric field of 16 kV/cm. The introduction of the ferroelectric tuning layer enhances the bandwidth of the VCLC in comparison with a Lange coupler with no ferroelectric layer. This work demonstrates another advantageous application for ferroelectric thin films in passive microwave components.**

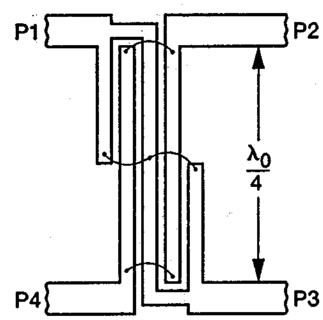
***Index Terms*—BSTO ferroelectric thin-film, K-band frequencies, microstrip Lange coupler, voltage-controlled couplers.**

I. Introduction

FREQUENCY and phase agility in planar microwave components can be realized using ferroelectric or ferrite-based thin films incorporated into conventional microstrip or coplanar waveguide circuits [1]–[4]. Room temperature tunable ferroelectric thin films such as $Ba_{0.6}Sr_{0.4}TiO_3$ (BSTO) are attractive for microwave components due to the nonlinear dc electric field dependence of their relative dielectric constant.It has been demonstrated that the relative dielectric constant of BSTO ($\varepsilon_{r\mathrm{BSTO}}$) could be reduced by more than a factor of 3 under the influence of a dc electric field at or near room temperature and microwave frequencies [5], [6]. Recently, we have demonstrated large frequency tunability in conductor/ferroelectric/dielectric two-layered microstrip bandpass filters at Ku- and K-band frequencies [7], [8]. In this work, we demonstrate a new application for ferroelectric thin films for enhancing the performance of a Lange coupler designed for K-band frequencies. A directional coupler is an essential component in balanced mixers, balanced modulators, and antenna feeds in communication systems. Microstrip Lange coupler is the most preferred planar coupler for tight coupling levels due to the wider spacing that is possible in the inter-digitated fingers, and its good isolation between ports compared to other types of planar couplers [9], [10]. Our objectives in this study were to determine the effects of dielectric tunability on the performance of the Lange coupler, especially the changes in the coupling level and the phase shift due to the dc electric field dependence of $\varepsilon_{r\mathrm{BSTO}}$.



(a)



(b)

Fig. 1. (a) Geometry of the conductor/ferroelectric thin film/dielectric two-layered microstrip structure. (b) Layout of the Lange coupler. Port 1 is the input port, port 2 is the coupled port, port 3 is the direct port, and port 4 is the isolated port. The width of the inter-digitated fingers (w) was 22 μm and the spacing between the fingers (s) was 25 μm. The input, coupled, direct and the isolated ports were designed for 50 Ω.

II. Coupler Design, Fabrication, and Testing

The voltage-controlled Lange coupler (VCLC) was designed for 3 dB coupling between 16 and 20 GHz, on 12 mil thick

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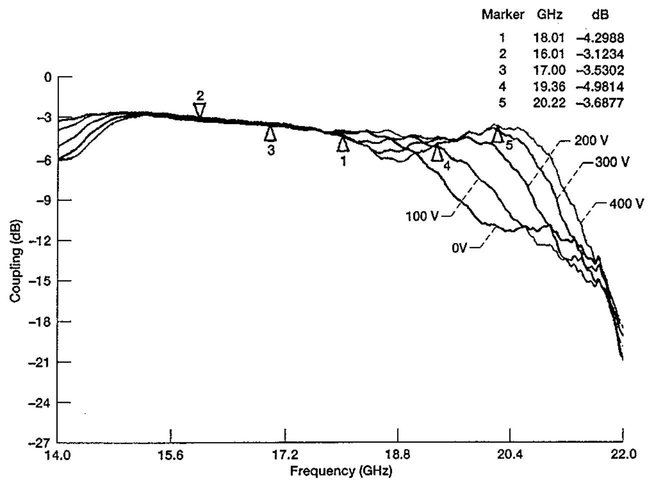

Fig. 2. DC bias dependence of coupling at room temperature for one of the VCLC's tested.

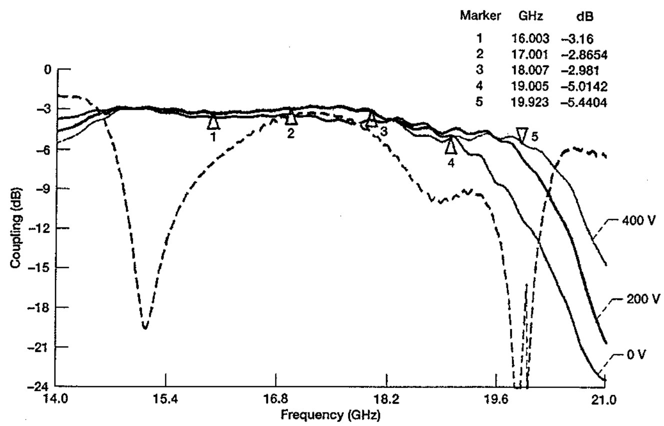

Fig. 3. DC bias dependence of coupling for another VCLC tested at room temperature. For comparison, a Lange coupler on a bare MgO is also shown (dashed line).

MgO substrates ($\varepsilon_r = 9.7$) with four inter-digitated fingers, using the two-layered microstrip structure shown in Fig. 1(a). The VCLC was designed for maximum enhancement in coupling level at K-band, assuming that the bias dependent $\varepsilon_{r\mathrm{BSTO}}$ changes between $\varepsilon_{r\mathrm{BSTO\ max}}$ of 1200 (at zero-bias) and $\varepsilon_{r\mathrm{BSTO\ min}}$ of 400 (at a maximum bias voltage of 400 V, corresponding to 16 kV/cm). This assumption is based on the latest values of $\varepsilon_{r\mathrm{BSTO}}$ reported in literature for BST thin films at GHz frequencies on lattice matched crystalline substrates such as $LaAlO_3$ and MgO [5], [6]. The coupler was designed using Sonnet em® design tools. The plan view for the coupler is shown in Fig. 1(b). Samples with 350 nm BSTO thin film on 12 mil thick MgO substrates were obtained from our collaborators at the University of Maryland, College Park. The 350 nm thick BSTO was deposited on MgO substrates using pulsed laser deposition technique. Note that although the BSTO covers the entire substrate, in principle, one may need BSTO only in specific areas, such as the spacing between the inter-digitated fingers where tunability will be effective. The VCLC circuits were fabricated on BSTO using standard lift-off photolithography. Typically alternate inter-digitated fingers are wire-bonded, as shown in Fig. 1(b), for maintaining them at the same potential, which, in turn, allows for improved coupling and bandwidth. In our case, the alternate fingers were not wire-bonded, for simplicity. Two dc power supplies were used for the full bipolar bias configuration, one for the positive voltage and the other for the negative voltage. The samples were tested at room temperature and under vacuum (<50 mtorr) in a cryostat to diminish any possibility of arcing at high bias voltages. Bias voltages up to ±400 V were applied to the VCLC with minimal power consumption (<2 mW). The swept frequency s-parameter measurements were performed using an HP8510 C automatic network analyzer (ANA).

III. Results and Discussions

The coupling of one of the VCLC's exhibited a bias dependence as shown in Fig. 2. At 0 V, the coupling was very close to 3 dB between 14 and 16 GHz, and the coupling rolled-off sharply beyond 18.5 GHz. A bias voltage was applied to the coupled and isolated ports with the input and direct ports held at ground potential. With an applied bias of 100 V, the coupling level improved above 18.5 GHz. At 400 V dc bias (16 kV/cm), the coupling level at 20 GHz showed an improvement closer to 8 dB, from −11.6 dB at zero bias to −3.68 dB at 400 V bias. Clearly, the bandwidth for the VCLC was enhanced, and so was the coupling level above 19 GHz. There exists a narrow region between 18 and 19 GHz where the coupling level had been suppressed by more than 1 dB. The origin for this is not known at the present time. Another VCLC exhibited close to 3 dB coupling from 14.7 to 18 GHz with applied bias greater than 200 V, and the coupling level improved by more than 6 dB at 20 GHz, at a dc bias voltage of 400 V, (16 kV/cm). For comparison, the coupling for a Lange coupler on a bare MgO substrate with no ferroelectric is also shown. The coupler on bare MgO exhibited a very narrow-band coupling behavior which could be improved by wire-bonding the alternate fingers. Clearly, for the same coupler, the ferroelectric thin film improves the bandwidth as is evident from Fig. 3. Also, it is evident that the coupling level can be voltage-controlled, as one might be able to bias the coupler to obtain exactly 3 dB coupling, as in Fig. 3, this being possible with the introduction of the voltage tunable ferroelectric layer. The coupler directivity (with input and direct ports left open) was better than 10 dB between 18 and 20 GHz with applied bias greater than 200 V (8 kV/cm). The isolation was better than 10 dB between 14 and 20 GHz.

Another feasible use for the VCLC is continuous phase shift using the bias dependence of $\varepsilon_{r\mathrm{BSTO}}$. With the application of a dc bias (for example, a positive voltage at the coupled and isolated sections, and negative voltage at the input and direct ports), we can vary the effective dielectric constant in the coupled section, resulting in a phase shift between any two ports. If we use the phase angle versus frequency data for the zero bias as the reference, one could obtain the phase shift for a specific bias condition by subtracting the phase angle at 0 V, at a specific frequency. Fig. 4 shows the relative phase shift versus frequency between input and coupled ports, showing that we could obtain a phase shift anywhere between 0 and 60° at 19.5 GHz for bias voltages 0 to ±400 V. The observed anomaly in the phase shift

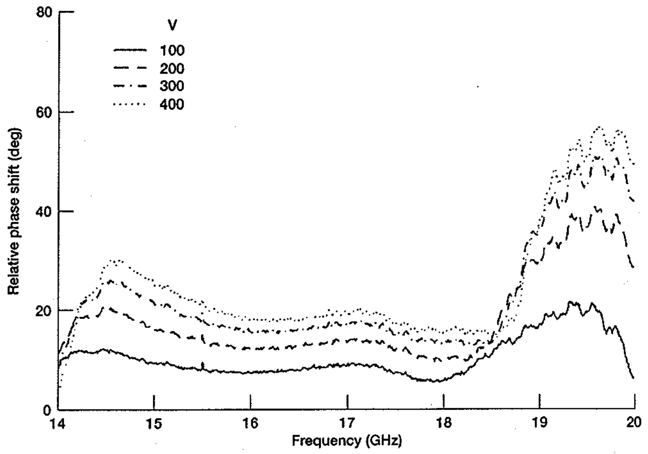

Fig. 4. DC bias dependence of relative phase shift between input and coupled ports at room temperature.

within the 19–20 GHz frequency range arises from an enhancement of the sensitivity of the coupling of the VCLC to the applied bias in that frequency region. The effect is not noticeable at the lower-end frequencies since at lower frequencies the coupling is barely sensitive to the applied bias (as shown in Fig. 2). Such smaller phase shifts although not useful for practical applications, demonstrates the dual nature of the VCLC. For the same bias voltages, thicker ferroelectric films are expected to provide larger phase shifts. Theoretical modeling using Sonnet em® predicts a phase shift as high as 360° for ferroelectric films (∼2000 nm thick), and a bias dependent change in $\varepsilon_{r\mathrm{BSTO}}$ of 3000 to 300 (10 : 1).

IV. Summary and Conclusions

In summary, a new voltage-controlled Lange coupler (VCLC) was designed, fabricated and tested for the first time, using a ferroelectric-tunable microstrip configuration. Experimental results indicate that the coupler offers wider bandwidth compared to the coupler with no ferroelectric tuning layer. The coupling level at K-band was voltage controllable, and could be improved by several dB using the dc electric field dependence of $\varepsilon_{r\mathrm{BSTO}}$. The coupler offers flexibility for fine-tuning using a dc bias. Another feature of such a coupler is continuous phase shift with applied dc bias. This work demonstrates a new and advantageous application for ferroelectric thin films in passive microwave components.

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