A *K*-Band Tunable Microstrip Bandpass Filter Using a Thin-Film Conductor/Ferroelectric/Dielectric Multilayer Configuration

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***Abstract*—We report on a gold/strontium titanate (Au/SrTiO$_3$) thin-film *K*-band tunable bandpass filter on a lanthanum aluminate substrate. The two-pole filter has a center frequency of 19 GHz and a 4% bandwidth. Tunability is achieved through the nonlinear temperature dependence and the dc electric field dependence of the relative dielectric constant of SrTiO$_3$. A center frequency shift of 0.85 GHz was obtained at 400-V dc bias and 77 K without degrading the insertion loss of the filter.**

***Index Terms*— Ferroelectric thin films, *K*-band frequencies, multilayer structures, tunable bandpass filters.**

I. INTRODUCTION

STRONTIUM TITANATE (STO) ferroelectric thin films have been intensely studied in recent years for possible applications in tunable microwave components such as varactors, phase shifters, resonators, and filters [1]–[6]. Its relative dielectric constant ($\epsilon_{r\text{STO}}$) varies nonlinearly from 300 at room temperature to values up to 3500 at temperatures below 80 K [5]. The increase (decrease) of $\epsilon_{r\text{STO}}$ will shift the center frequency of a filter to lower (higher) frequencies, allowing tuning of the filter. It has been demonstrated that the STO films can be tuned advantageously at temperatures below 100 K [5]. For example, at temperatures near 77 K, $\epsilon_{r\text{STO}}$ could be reduced by more than a factor of five under the influence of a dc electric field [5]. This drop in $\epsilon_{r\text{STO}}$ will lower the effective dielectric constant of the multilayered structure, shifting the passband upward. For a bandpass filter, the tunability factor is defined as the ratio of change in center frequency to the actual center frequency. A HTS/STO/Lanthanum aluminate (LaAlO_3) coplanar bandpass filter designed for 2.5 GHz has been demonstrated by Findikoglu *et al.* [6]. This filter exhibited a tunability factor over 15% and showed improved filter characteristics with biasing. However, it remains to be seen if this technology can be exploited favorably at *K*-band and higher frequencies where new developments in satellite communications are currently in progress [7]. This letter reports on the performance of a *K*-band tunable microstrip bandpass filter using a Au/STO thin-film structure. This filter can be used in satellite communication subsystems such as a receiver front-end. To our knowledge, this is the first demonstration of a conductor/ferroelectric thin-film microstrip tunable filter at K-band frequencies.

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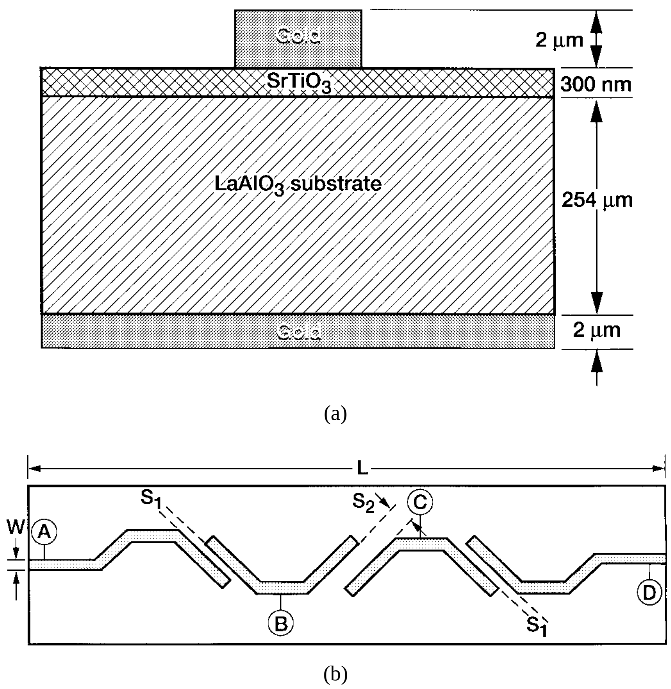

Fig. 1. (a) Cross section of the multilayered microstrip structure. (b) Layout of the two-pole microstrip bandpass filter designed for 19 GHz. The dimensions are: $W = 86.25\ \mu$m, $L = 6.8$ mm, $S_1 = 100\ \mu$m, $S_2 = 300\ \mu$m.

II. DESIGN OF THE TUNABLE MICROSTRIP FILTER

The two-pole bandpass filter was designed using microstrip edge-coupled half-wavelength resonators [8]. The filter was designed for a center frequency of 19 GHz, with 4% bandwidth and a passband ripple below 0.5 dB. The cross section of the multilayered microstrip structure and the overall filter circuit layout are shown in Fig. 1. The multilayered microstrip structure consists of LaAlO_3 substrate (254 μm thick), a 300-nm thin-film STO layer, and a 2-μm gold thin film for the microstrip and the ground plane. The design was performed using standard microstrip calculations and coupled sections, with suitable compensation for odd- and even-mode impedances [9]. This initial design resulted in an overestimation by approximately 15% in width, spacing, and length of coupled sections. The optimal design was achieved using Sonnet's

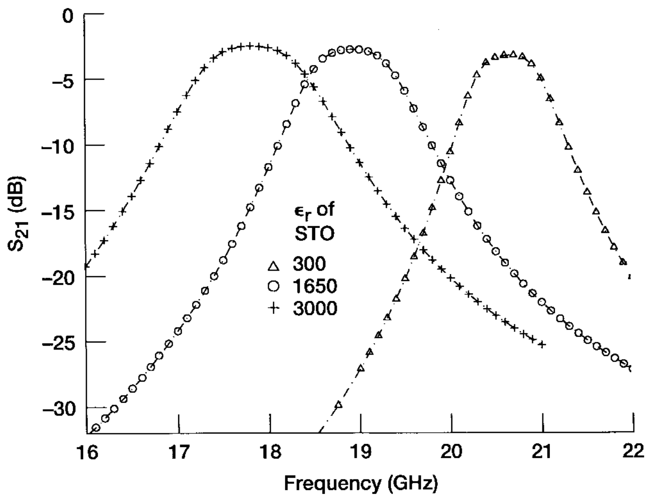

Fig. 2. Sonnet em® simulation results for the two-pole bandpass filter as a function of $\epsilon_{r\mathrm{STO}}$.

em® simulator [10]. To obtain narrow bandwidth, the distance between the input and the output is stretched using angled microstrip coupled sections as shown in the layout in Fig. 1(b). The Sonnet em simulation results for the gold/STO/$\mathrm{LaAlO_3}$ multilayered microstrip bandpass filter are shown in Fig. 2, for the cases of $\epsilon_{r\mathrm{STO}}$ equal to 300, 1650, and 3000. The filter's insertion loss (2.5 dB at room temperature) did not change appreciably as the $\epsilon_{r\mathrm{STO}}$ was changed from 300 to 3000. The filter was designed to operate at a center frequency corresponding to an $\epsilon_{r\mathrm{STO}}$ of 1650. By keeping the temperature constant, (e.g., 77 K) and varying the dc electric field, the passband of the filter can be shifted up or down in frequency. As shown in Fig. 2, the center frequency changes from 17.5 to 20.75 GHz, a tunability factor of 15%, with no appreciable change in the insertion loss. The return loss in the passband was near or better than 20 dB for all three cases. The bandwidth increased to slightly greater than 5% for $\epsilon_{r\mathrm{STO}}$ of 3000.

III. Experimental

The STO thin films used in this study were obtained from Superconductor Core Technologies (SCT), Golden, CO. The STO thin films were deposited on the $\mathrm{LaAlO_3}$ substrate using a laser ablation technique. The STO films were post annealed at 1200 °C for 7 h to improve film quality [5]. The gold microstrip bandpass filter circuit was fabricated at Lewis Research Center (LeRC) using lift-off photolithography technique. A 2-μm gold ground plane was deposited using e-beam evaporation to complete the circuit fabrication. The circuits were packaged for testing the temperature and dc field dependence of the filter's swept frequency S-parameters. Cryogenic characterization was performed using a helium gas closed-cycle refrigerator and an HP-8510 C vector analyzer [5].

IV. Results and Discussions

At room temperature, one of the gold filters exhibited the transmission and reflection characteristics shown in Fig. 3. The insertion loss of the circuit was below 3.5 dB through the entire passband. The return loss in the passband was between 8 and 15 dB. The bandwidth of the filter was approximately 7%. The center frequency was 19.33 GHz. As the temperature was lowered, the filter exhibited superior performance compared to that at room temperature (see Fig. 4). The results in Fig. 4 are remarkable in the sense that the insertion loss in the passband in the worst case (i.e., at 296 K) was still below 2.5 dB, very similar to the theoretical simulation results of Fig. 2. The return loss in the passband also improved at low temperatures, to greater than 20 dB (see the dashed line in Fig. 4). The only degradation caused by the large $\epsilon_{r\mathrm{STO}}$ is the larger bandwidth at 50 K. Note that the temperature variation induced shift in center frequency is from 19.33 GHz at 296 K to 17.0 GHz at 50 K, approximately 12% tunability. The improvement in insertion loss and return loss are mainly due to the lower conductor losses at low temperatures. The dc electric field dependence of the filter's response was tested at two temperatures, 77 and 40 K. Referring back to Fig. 1, the nodes A and C were connected to the positive terminal of the dc high voltage power supply, and the nodes B and D were connected to the ground. The dc bias was increased from 0 to 400 V in steps of 100 V. The field dependence of the filter's S_{21} at 77 K is shown in Fig. 5. Note that the insertion loss improved as the bias was increased, because of reduction in dielectric losses in the STO as a function of bias. The poorer

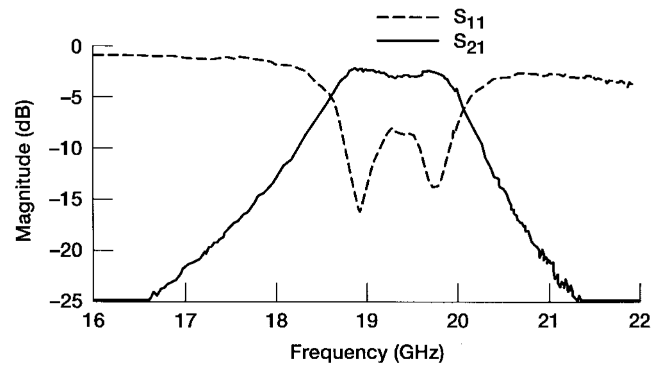

Fig. 3. Measured S_{21} and S_{11} response of the filter at room temperature.

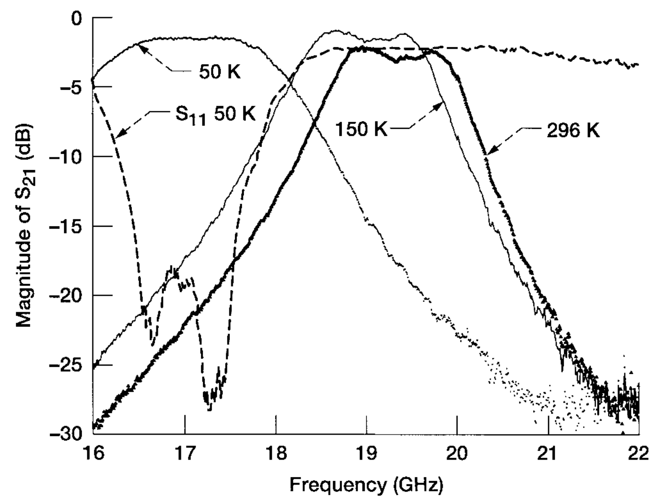

Fig. 4. Temperature dependence of the magnitude of S_{21} for the filter at zero bias. Also shown in the same scale are S_{11} data for 50 K.

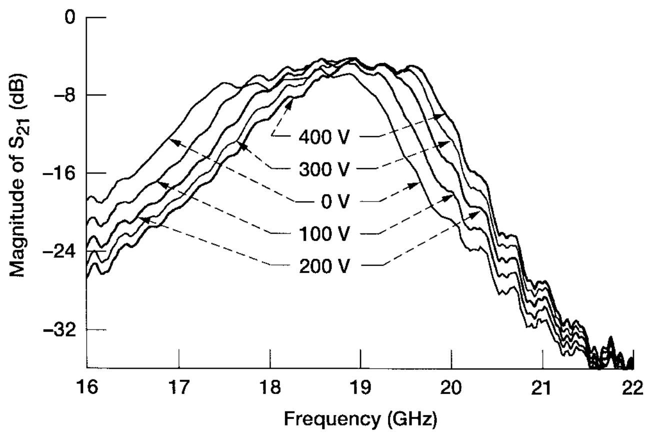

Fig. 5. The bias dependence of the magnitude of S_{21} at 77 K.

response of the filter with respect to that shown in Fig. 4 is due to the wire bonding required for bias. The bandwidth of the filter was larger with zero bias, approximately 7.5%, compared to the maximum applied bias of 400 V, approximately 5%. The center frequency of the circuit shifted from 18.3 GHz at no bias, to 19.15 GHz at 400 V bias, indicating a tunability factor greater than 4% at 77 K. The tunability factor improved to 8% at 40 K, indicating a larger change in $\epsilon_{r\mathrm{STO}}$. Use of HTS thin films with lower microwave conductor losses with respect to the normal conductors and thin-film STO will prove to be an excellent combination for realizing planar and quasiplanar tunable components, circuits, and systems. A tunable HTS/ferroelectric thin-film-based microstrip bandpass filter is currently being investigated at LeRC.

V. Summary and Conclusions

In summary, a planar tunable microstrip bandpass filter with low insertion loss has been realized using nonlinear dielectric STO ferroelectric thin film. Experimental results indicated 12% tunability using the temperature dependence of the $\epsilon_{r\mathrm{STO}}$ and approximately 4% tunability at 77 K using the electric field dependence of the $\epsilon_{r\mathrm{STO}}$. This is the first experimental verification of a tunable conductor/ferroelectric thin-film planar microstrip filter at K-band frequencies.

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