Design and Development of Ferroelectric Tunable Microwave Components for Ku- and K-Band Satellite Communication Systems

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***Abstract*—Integration of a high-temperature superconductor with a nonlinear dielectric ferroelectric such as strontium titanate, i.e., $SrTiO_3$ (STO), has created a new class of electrically tunable low-loss microwave components. We have designed and fabricated frequency and phase agile components using a conductor/ferroelectric/dielectric two-layered microstrip configuration. Some examples of these components are: microstrip ring resonators, local oscillators, edge coupled filters, and phase-shifter circuits. These structures have been fabricated using $YBa_2Cu_3O_{7-\delta}$ or gold conductor-based microstrip lines fabricated on lanthanum aluminate ($LaAlO_3$) or magnesium oxide (MgO) substrates coated with an STO thin film. Frequency and phase agility are achieved using the nonlinear dc electric-field dependence of the relative dielectric constant of STO ferroelectric thin film ($\epsilon_{r\mathrm{STO}}$). In this paper, we will present an assessment of the progress that our group has achieved thus far toward integration of this technology into wireless and satellite communication systems.**

***Index Terms*—Ferroelectric, high-temperature superconducting, K-band, Ku-band, microwave, tunable.**

I. Introduction

PLANAR microstrip high-temperature superconductor (HTS) circuits are attractive for communication applications due to their lower conductor losses compared to normal conducting circuits at cryogenic temperatures. A variety of HTS circuits have been demonstrated in the past decade, such as resonators, filters, and phase-shifting circuits aimed at high-performance (i.e., selectivity, low noise, and low-insertion loss) communication systems [1], [2]. The demand for high bandwidth continues to grow due to the latest developments in internet and wireless communication technology. Even more applications such as remote sensing and broad-band low Earth orbit (LEO) satellite systems are evolving at frequencies above the traditionally used C-band (~4–8 GHz) in which the integration of HTS is attractive due to the low-loss HTS thin films currently available [3], [4]. Among the HTS components that are useful for the communication industry are high-Q planar microstrip resonators, filters, phase shifters, and highly directive antennas. For example, microstrip ring resonators are widely used in microwave electronics, both as a characterization tool as well as critical components in high-frequency communication systems. Ring-resonator-based filters and stabilizing ring resonator elements in local oscillators (LO's) are two common applications of ring resonators [5], [6]. Another important HTS circuit with potential advantageous applications in the wireless and satellite communication industry is the pre-select filter in receiver front-ends [3], [4]. Initial applications of the HTS thin-film microstrip filters have been successful, exhibiting superior performance (e.g., lower insertion loss and steeper out-of-band rejection) than their metallic counterparts. However, it is known that for most filters and other resonant structures, attainment of optimal performance requires some level of additional tuning either through mechanical means (i.e., with tuning screws) or other coupling mechanisms. Therefore, if electronic tuning is incorporated into HTS components without degrading performance, the result will be low-loss microwave components that could be fine tuned for optimal performance or, alternatively, could be tunable over a broad-band frequency range. This approach will greatly improve the utility of HTS circuits.

Frequency and phase agility in microwave circuits can be realized using ferroelectric- or ferrite-based thin films incorporated into conventional microstrip circuits [7]–[10]. Novel superconductor-ferrite phase shifters and circulators with magnetic confinement have been demonstrated [8]. However, usage of ferrite thin films requires external coils and typically large currents for tunability. Ferroelectric thin films are suitable for frequency-agile microwave components due to the nonlinear dc electric-field dependence of their relative dielectric constant. The tunability (τ) of such a film is given by the change of the relative dielectric constant of the ferroelectric under an external dc field (ϵ_{rE}) with respect to that at no field (ϵ_{r0}), divided by $\epsilon_{r0}(\tau = (\epsilon_{rE} - \epsilon_{r0})/\epsilon_{r0})$. For a filter, one can define a frequency tunability factor (τ_F) as the ratio of the change in center frequency to the original center frequency, i.e., $\tau_F = \Delta f/f_o = (f_{V\max} - f_o)/f_o$, where f_o is the center frequency of the frequency agile component at no bias and $f_{V\max}$ is the center frequency of the component at the maximum applied bias.

Strontium titanate (STO) and barium strontium titanate ($Ba_xSr_{1-x}TiO_3$), henceforth referred to as BSTO, are two

Manuscript received April 17, 1999; revised January 13, 2000. The work of G. Subramanyam was supported by NASA/OAI under 1997, 1998, and 1999 Summer Faculty Fellowships. The work of F. W. Van Keuls and C. H. Mueller was supported by the National Research Council under a fellowship. An earlier version of this paper was presented at the 1998 and 1999 IEEE MTT-S International Microwave Symposia.

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Publisher Item Identifier S 0018-9480(00)05540-X.

of the most popular ferroelectric thin films currently being studied for frequency-agile components and circuits. It has been demonstrated that the STO's relative dielectric constant ($\epsilon_{r\mathrm{STO}}$) could be reduced by over a factor of five under the influence of a dc electric field below 77 K [11]. A $YBa_2Cu_3O_{7-\delta}$(YBCO)/STO/$LaAlO_3$ (LAO) coplanar bandpass filter designed for 2.5 GHz has been demonstrated by Findikoglu *et al.* [12]. A large tunability factor above 15% was demonstrated in these filters and the results indicated that tuning resulted in improved filter characteristics. Concomitantly, our group has demonstrated frequency tunability in resonators and bandpass filters using the YBCO/STO/LAO two-layered microstrip structure at Ku- and K-band frequencies [13], [14]. We have also demonstrated Ku-band YBCO/STO/LAO coupled microstripline phase shifters (CMPS's) with over 360° of contiguous phase shift with 5-dB nominal loss. These components allow development of a new class of electrically tunable circuits for communication systems. Attributes such as small size, light weight, and low loss make these components very attractive not only for NASA's communication systems, but also for applications in the commercial communication industry at large. Our paper addresses a variety of aspects relevant to optimal performance of ferroelectric tunable microstrip components such as design, dc biasing, and performance analysis. In this paper, we will present an assessment of the progress that our group has achieved thus far toward integration of this technology into wireless and satellite communication systems.

II. Design and Experiment

The cross section of the two-layered microstrip structure used in various components is shown in Fig. 1. The modified microstrip structure consists of a dielectric substrate (LAO or MgO, typically 254-μm thick), a ferroelectric thin-film layer (thickness "t" varying from 300 to 2000 nm for various applications), a gold or YBCO thin film 2-μm thick or 350-nm thick, respectively) for the top conductor, and a 2-μm-thick gold ground plane. The dielectric properties of the ferroelectric thin film and the thickness of the ferroelectric film play a fundamental role on the frequency or phase tunability and the overall insertion loss of the circuit. We have studied the geometry of the multilayered microstrip by performing electromagnetic simulations with Sonnet em and the Zeland's IE3D software to obtain the relationships between parameters such as the characteristic impedance (Z_o), effective dielectric constant (ϵ_{eff}), and attenuation (α) as a function of frequency, temperature, linewidth-to-substrate's height ratio (W/H), ferroelectric film thickness (t), and the relative dielectric constant and loss tangent of the ferroelectric thin film (ϵ_r, and $\tan\delta$, respectively). These simulations have been found to be in reasonable agreement with modeling using a quasi-TEM variational analysis [15]. The results of the modeled microstrip structure have been presented elsewhere [16]. Important results are summarized in this paper. For a given value of $\tan\delta$, α becomes larger at higher frequencies, and for a given frequency it becomes larger as the value of $\tan\delta$ increases. Also, for a given frequency and $\tan\delta$ value, α increases with film thickness.

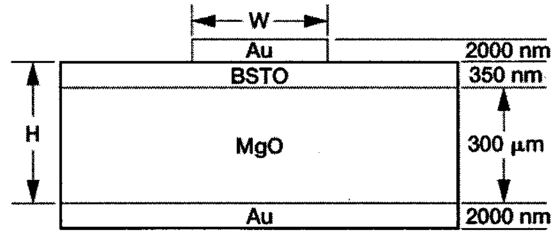


Fig. 1. Cross section of the two-layered microstrip structure used in various components. The modified microstrip structure consists of a dielectric substrate (LAO or MgO typically 254–508-μm thick), a ferroelectric thin-film layer (thickness "t" varying from 300 to 2000 nm for various applications), a gold or HTS thin film (2-μm thick or 350-nm thick, respectively) for the top conductor, and a 2-μm-thick gold ground plane.

Also, as the value of the ϵ_r of the ferroelectric film increases, α increases. This increase is a consequence of mismatches resulting from the decrease in Z_o and the increase in ϵ_{eff} with increasing ϵ_r, and the unavoidable correlation between ϵ_r and $\tan\delta$. For all ferroelectric tunable devices, the mismatch and insertion losses vary as the dc tuning voltage is varied. For some devices, the insertion loss due to the ferroelectric can be less than the conductor loss. However, in general, greater tunability leads to greater maximum loss found within the tuning range.

The fabrication and testing of the tunable microwave devices have been discussed elsewhere [5], [6], [11], [13], [14]. Briefly, the ferroelectric films considered here have been deposited by pulsed laser deposition (PLD) on LAO and MgO substrates and have thicknesses within the 0.3–2.0-μm range. The YBCO HTS thin films were deposited by PLD as well. The gold (Au) metallization was done using electron-beam evaporation. The microwave testing of the devices was performed under a vacuum of less than 1 mtorr, with the samples mounted on the cold finger of a helium gas closed-cycle refrigerator via a custom-made test fixture. The microwave characterization was performed using an HP-8510-C Automatic Network Analyzer to measure the reflection and transmission scattering parameters (S_{11} and S_{21}, respectively). When necessary in the tunable filters, application of large dc voltages to the microstrip transmission lines was achieved through the SMA launchers using custom-made bias tees designed to withstand the application of up to 700 V dc at K-band frequencies [17].

III. Results and Discussions

A. Tunable Ring Resonators

At the NASA Glenn Research Center, Cleveland, OH, we have investigated ring resonator configurations using Au/STO/LAO and YBCO/STO/LAO conductor/ferroelectric/dielectric (CFD) structures at Ku- and K-band frequencies (see Fig. 1). Microstrip side-coupled ring resonators were used in our study, as shown in Fig. 2. Two ring resonators with characteristic impedances of 50 and 25 Ω were designed for third-order resonance at 20 GHz (with no ferroelectric layer) to avoid moding problems. Under appropriate biasing schemes, these "band-stop" resonators exhibit sharp resonances with unloaded Q $(f_o/\Delta f_{3\,\mathrm{dB}})$ as high as 15 000. The resonant frequency has been tuned beyond 1 GHz (e.g., 16.6 GHz at

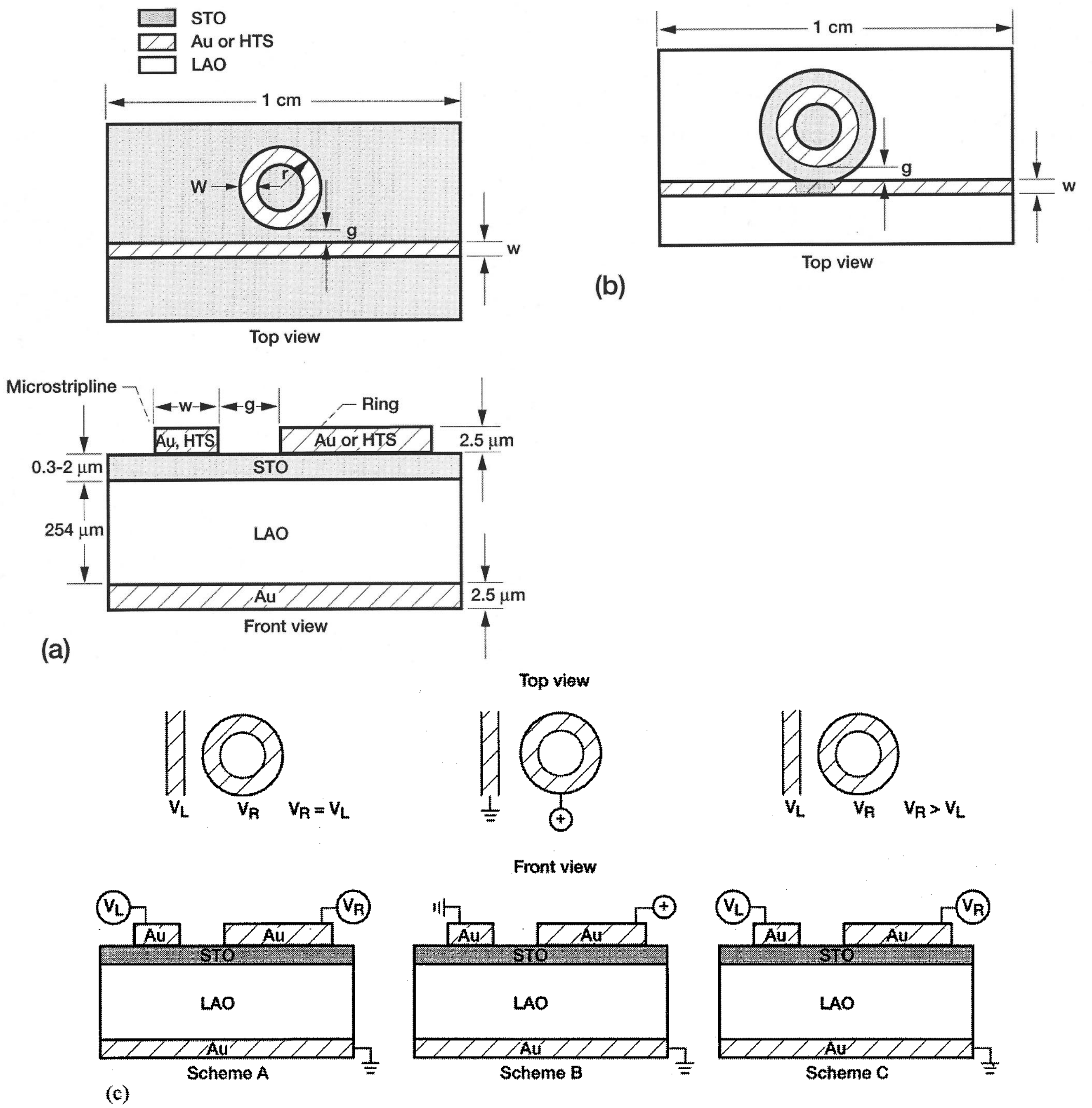


Fig. 2. Microstripline side-coupled 25-Ω ring resonator. $W = 406$ μm, $w = 89$ μm, $r = 1694$ μm, and $g = 25$ μm. (b) shows the condition when the ferroelectric in the circuit is limited only to the areas underneath the ring. (c) shows the various biasing schemes employed in our study.

zero bias to nearly 17.8 GHz at a dc voltage of 400 V) without degrading the sharpness of the resonance (see Fig. 3). The effect of the applied dc electric field on the parameters such as the insertion loss, center frequency, return loss, and unloaded Q of the microstrip resonators have been studied experimentally [5]. In the resonators, by choosing the right biasing scheme and adjusting two independent dc voltages, one can optimize the coupling and sharpen the resonance while maintaining large tunabilities, as shown in Fig. 3. The various biasing schemes studied are also shown in Fig. 2. Changing the dc voltage on the ring V_R mainly changes the ϵ_{eff} of the ring and its resonant frequency. The voltage difference $V_R - V_L$ controls the coupling of the ring to the line, allowing one to tune the resonator from over coupled, through critical, to under coupled. Maximum coupling to the ring was obtained using the biasing scheme A ($V_R - V_L = 0$), which resulted in higher frequency tunability, but over-coupled resonances having low-Q values. Biasing scheme B allows one to tune for a critical coupling and a sharp resonance, but only in a narrow range of frequency. By adjusting both V_R and V_L simultaneously (bias scheme C), one can optimize the coupling and sharpen the third-order resonance while maintaining large frequency tunability. The magnitude of S_{21} for this differential biasing scheme is shown in Fig. 3. The data shown in Fig. 3 exhibit sharp band-stop

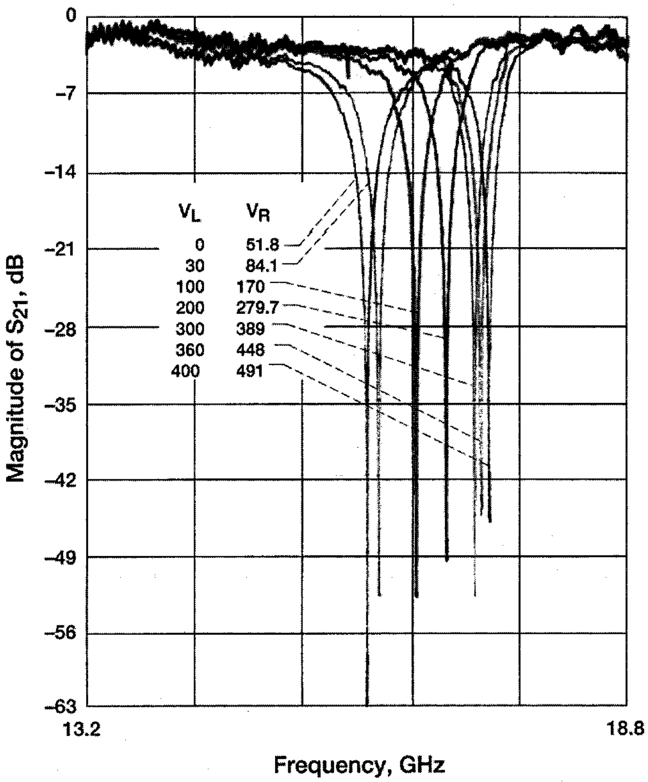


Fig. 3. Effect of dc bias on the 3λ ring resonant frequency and Q of the Au (2 μm)/STO (2 μm)/LAO (254 μm) ring resonator at 77 K and for the ring and line dc voltage values (V_R and V_L, respectively) shown in this figure.

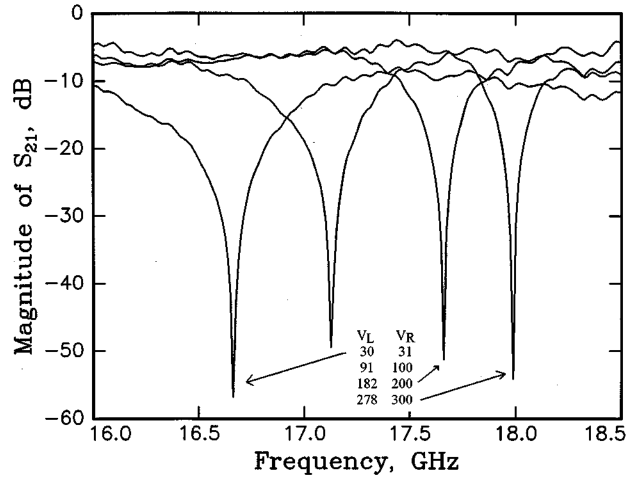
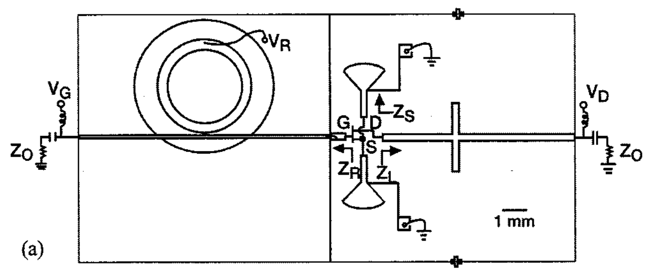
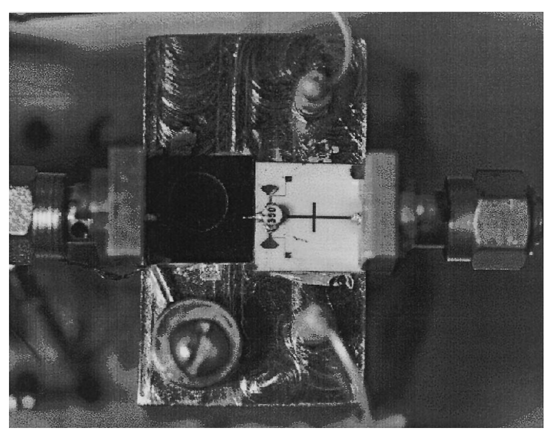


Fig. 4. Data from a second tunable ring resonator of the same design using a YBCO (0.35 μm)/STO (1 μm)/LAO (254 μm) circuit at 77 K. The ring and line dc voltage values (V_R and V_L, respectively) are shown in the figure.



(a)



(b)

Fig. 5. (a) Layout of the complete VCO showing the ring resonator portion as well as the pHEMT portion. As discussed, the pHEMT portion is fabricated on an alumina substrate. (b) Actual circuit.

characteristics with unloaded Q values as high as 15 000. Fig. 4 shows data from a ring resonator of the same dimensions using a YBCO/STO/LAO structure. The resonators of Figs. 3 and 4 also differ in that the Au resonator had the STO etched in the region beyond 2 mm from the ring [see Fig. 2(b)], while for the YBCO resonator, the STO was not etched.

These results must be discussed in the context of the performance of dielectric-resonator oscillators (DRO's), which represent current state-of-the-art at high frequencies. Reported values for DRO's unloaded quality factor (Qo) have been as high as 50 000 at 10 GHz [18]. However, their manufacturing cost, lack of electronic tunability, and nonplanar geometry limits their versatility for insertion in frequency agile communication systems such as tunable LO's, broad-band band-stop filters, and "notch" filters for wireless communications [19].

B. Tunable LO's

A key parameter of modern digital communication systems is the phase noise. Phase noise is introduced into a system primarily by the LO used in a receiver. Currently, there are several ways to achieve stabilization of an LO. However, all of these approaches have intrinsic limitations. Crystal stabilized oscillators represent the state-of-the-art at low frequencies. However, they are generally restricted to frequencies below several gigahertz. DRO's are commercially available up to at least 20 GHz, but do not lend themselves to electronic tuning or frequency locking. Further, their fabrication must be done independently of the oscillator circuit, and its three-dimensional geometry is not conducive to the fast and high volume production of the optimized circuit. As a viable alternative, we have fabricated a tunable LO using a 0.25-μm gate-length pseudomorphic high electron-mobility transistor (pHEMT) (ATF-35076) as the active component and a novel ferroelectric tunable microwave ring resonator with a center frequency of 16.7 GHz at zero bias as the passive component (see Fig. 5). To the best of our knowledge, our prototype represents the first time that a tunable oscillator based on thin-film ferroelectric structures has been demonstrated at such a high frequency. The circuit consists of a 25-Ω ring resonator side coupled using a microstrip feed line, and the pHEMT

(Avantek/HP 0.25 um ATF-35076) portion of the voltage-controlled oscillator (VCO) with appropriate impedance-matching networks constructed on 0.25-mm-thick alumina. The ferroelectric tunable ring resonator is similar to the ones discussed in the previous section. The pHEMT was characterized at 77 K, using an on-wafer coplanar waveguide probe, before designing the VCO. The pHEMT was unconditionally stable at 77 K with a gain of approximately 7 dB at 16.7 GHz. An inductor was inserted between the source and ground to make the device unstable, by using a section of a 50-Ω microstrip line 1.08-mm long. An iterative computer routine was used for choosing the source impedance (Z_s) to maximize the negative resistance of the pHEMT while preserving the loop gain. With a Z_s of $j35\ \Omega$, a stability factor (K) of -0.499 was obtained. More details of the design are published elsewhere [6]. During operation, the ring was dc biased at a bias in the range from 0 to 250 V with the bias on the microstrip kept at 0 V. With this biasing scheme, the gate and ring could be decoupled. An operating temperature of 43 K was chosen to maximize the electric-field induced tunability of STO. Both the ring resonator and pHEMT circuit were packaged on a brass fixture with conductive epoxy for testing inside an He-gas closed-cycle cryogenic system. By applying 38-V dc to the ring, the oscillator frequency was tunable by about 100 MHz around the center frequency (see Fig. 6). The figure shows the broad-band and narrow-band measurements done at 43 K with the drain bias at 2.1 V and the gate bias of -0.2 V. By increasing the ring voltage to 250 V, the tuning range was extended over 500 MHz. The merits of this VCO are its high-performance potential, small size, simplicity of implementation, and its potential for low-cost and high-volume production.

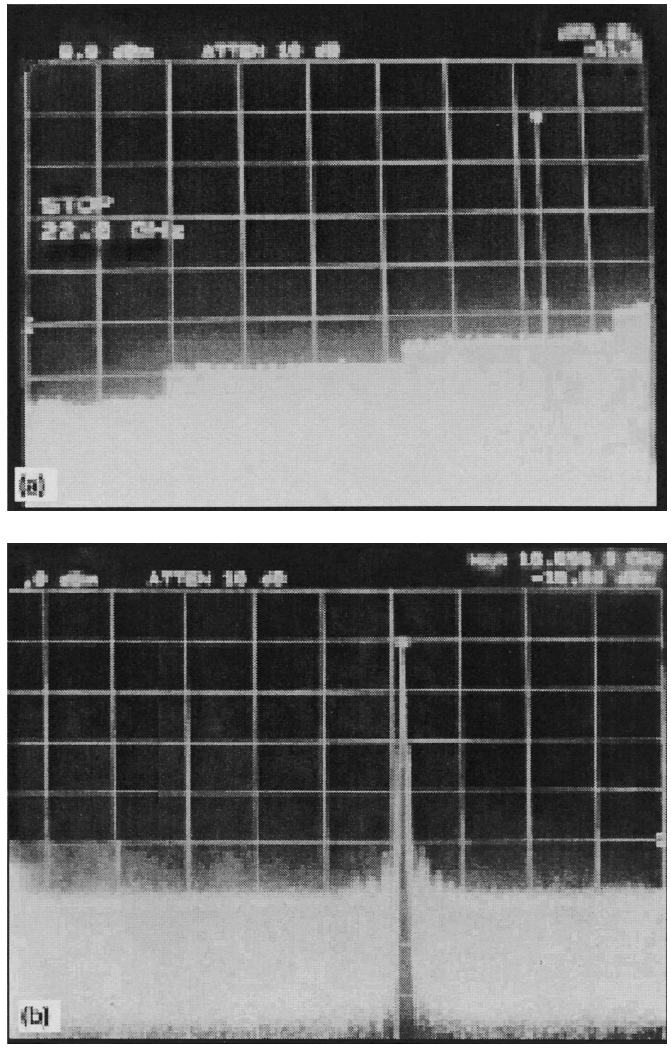


Fig. 6. VCO signals as measured on an HP 8566B Spectrum Analyzer at 43 K with: $V_d = 2.1$ V, $V_g = -0.2$ V, $I_d = 13.9$ mA, and $V_{\rm ring} = 38$ V. The scale on (a) is 2–22 GHz. (b) 500-MHz span with oscillation frequency at 16.696 MHz.

C. Tunable Filters for Cryogenic Applications

Another important component that can benefit from the ferroelectric thin-film technology is the pre-select filter in the receiver front-end. We have designed, fabricated, and tested YBCO/STO HTS/ferroelectric thin-film-based K-band tunable microstrip band pass filters on LAO dielectric substrates [13]. The layout of the filter is shown in Fig. 7. The two-pole filter was designed for a center frequency of 19 GHz and a 4% bandwidth, using the parallel coupled half-wavelength resonators. The design of the filters is discussed elsewhere [13], [14]. In these ferroelectric tunable filters, one can reduce the insertion loss of the passband or maintain the passband relatively unchanged over a tunable frequency range, depending on the biasing scheme employed. The following three biasing schemes have been studied to date:

1) unipolar bias (UPB), where alternate nodes were biased positive and ground;
2) partial bipolar bias (PBB), where input and output lines were grounded, and the resonator sections biased positive and negative alternatively;
3) full bipolar bias (FBB), where alternate sections (including the input and output lines) were biased positive and negative.

It is important to note that the effective dielectric constant of the microstrip structure depends upon the electric field between

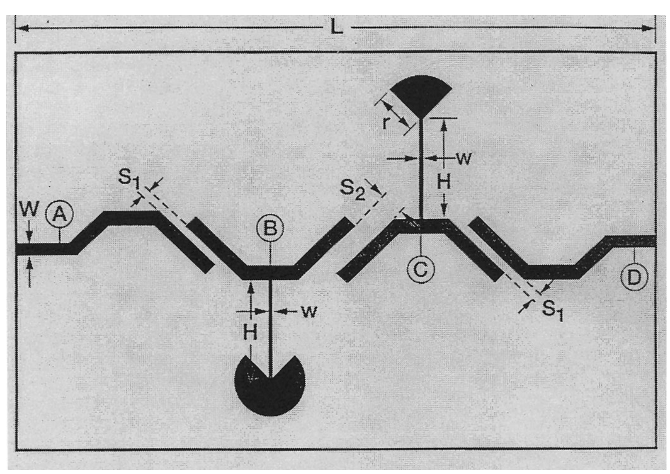


Fig. 7. Schematic of a tunable bandpass filter circuit. The dimensions are: $W = 86.25\ \mu$m, $L = 6.8$ mm, $S_1 = 100\ \mu$m, $S_2 = 300\ \mu$m, $H = 1.33$ mm, $w = 12.5\ \mu$m, and $r = 200\ \mu$m.

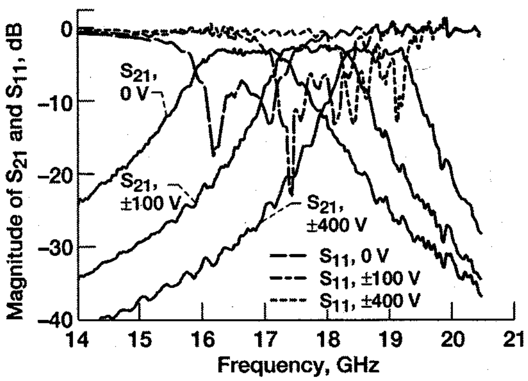


Fig. 8. Voltage dependence of the magnitude of S_{21} and S_{11} for YBCO/STO/LAO bandpass filter at 30 K showing the relatively unchanged passband throughout the tuning range.

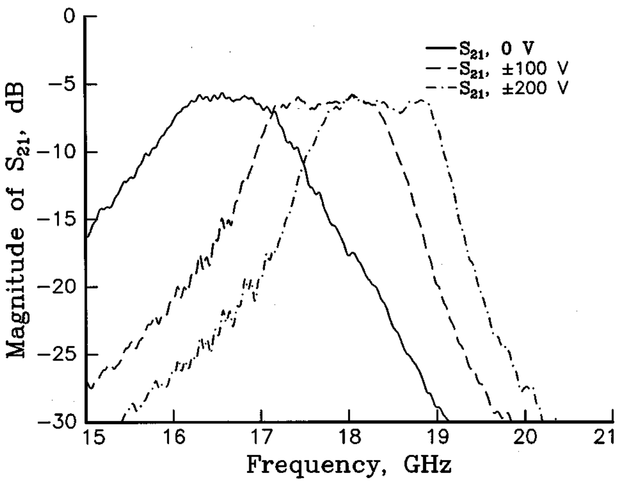


Fig. 9. Voltage dependence of the magnitude of S_{21} and S_{11} for a Au/STO/LAO bandpass filter at 40 K. The insertion loss of the filter is approximately 6 dB compared to less than 3 dB for the HTS counterparts.

the coupled microstrip lines as well as the perpendicular field between the top conductor and ground plane. In general, the FBB configuration gives the largest frequency tunability due to higher electric fields that can be applied in this configuration, and the PBB gave the lowest insertion loss in the passband in the ferroelectric tunable microstrip filters. Large tunability does not necessarily give the lowest insertion loss for the filters. A large frequency tunability of greater than 10% was obtained in YBCO/STO/LAO microstrip bandpass filters operating below 77 K. The dc electric-field dependence of one of the filters tested is shown in Fig. 8. A center frequency shift of 2.3 GHz was obtained at a 400-V bipolar dc bias and 30 K with minimal degradation in the insertion loss of the filter. The filter's passband shifted from a center frequency of 16.5 GHz at no bias to 18.8 GHz at the maximum applied bias of ±400 V, a tunability factor greater than 12%. The filter's passband insertion loss remained relatively the same through the tuning range. Remarkably, all of the filters tested to date have shown large tunability factors ($\geq$9%) at and below 77 K.

For comparison, Au/STO/LAO microstrip filter circuits were tested for electrical tunability at temperatures below 77 K. Fig. 9 shows the electrical tunability of an Au/STO/LAO biased using the bipolar biasing scheme. A tunability of approximately 11% was obtained at 40 K and at a dc bias of ±200 V. This tunability is comparable to that exhibited by the YBCO/STO/LAO filters. The insertion loss exhibited by this filter was approximately 6 dB, compared to less than 2 dB for HTS counterparts. The unloaded Q of the HTS resonator sections in the filters was estimated to be approximately 200 based on the model given in [20], which could possibly be improved by process optimization. The major limiting factor for the unloaded Q is the dielectric losses in the STO layer. Measurements of $\tan\,\delta$ values for laser-ablated STO thin films at cryogenic temperatures and gigahertz frequencies range from 0.005 to 0.05 [21], [22]. An important finding was that the percentage tunability remained essentially the same for a specific applied electric field, irrespective of the biasing scheme employed [23]. This finding created two new parameters called the sensitivity parameter (S) and loss parameter (L). The sensitivity parameter is defined as the slope of the frequency shift versus peak dc electric field.

Higher sensitivity parameter and lower loss parameter indicates larger frequency tunability combined with lower insertion loss for the filters. These parameters are very useful for evaluating the material quality, as one could compare geometrically different tunable components for both sensitivity and loss parameters.

The impact of these filters can be evaluated at the component level, as well as the subsystem level. At the component level, the filter's frequency agility allows for adjusting for Doppler effects, frequency hopping, and other communication applications requiring the filter's passband reconfiguration. In addition, using a single tunable filter instead of fixed frequency filter banks can add system flexibility. Also, low cost, ease of fabrication, and planar geometry make this filter technology very appealing for insertion into satellite receiver front-ends. The added flexibility may warrant the slightly increased insertion loss for some applications.

D. Coupled CMPS's

Another area of application of the ferroelectric thin-film technology is the fabrication of compact low-loss phase shifters. In general, phase-shifting elements can be realized through the use of ferrite materials, monolithic microwave integrated circuits (MMIC's), and diodes (e.g., switched line, reflection, and loaded line). Typically, diode or MESFET-based phase shifters are digital with phase bits of 11.25°, 22.5°, 45°, 90°, and 180°. Losses increase with the number of bits ($\sim$2 dB/bit) and the discrete phase shift steps sometimes result in scanning granularity. Unfortunately, MMIC technology has not yet met the expectations of lower cost for phased-array applications. Despite their high cost and poor efficiency of power amplifiers ($\sim$15%), MMIC's remain the technology of choice for K- and Ka-band phased arrays. We have developed a new class of low-cost and reliable phase shifters based on ferroelectric thin-film technology. Due to the configuration of its main phase-shifting element, we refer to this phase shifter as the CMPS. Fig. 10 shows the schematic of an eight-element K-band CMPS fabricated with an YBCO (0.35-μm thick)/STO (1-μm thick)/LAO (254-μm thick) two-layered microstrip structure. A coupled microstrip line, which can be excited

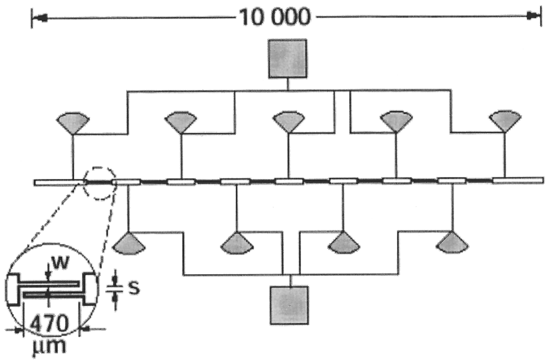


Fig. 10. Schematic of an eight-element CMPS on a 254-μm-thick LaAlO3 substrate. $S = 7.5$ μm and $W = 25$ μm. The microstrip lines are 84-μm wide. All units are in micrometers.

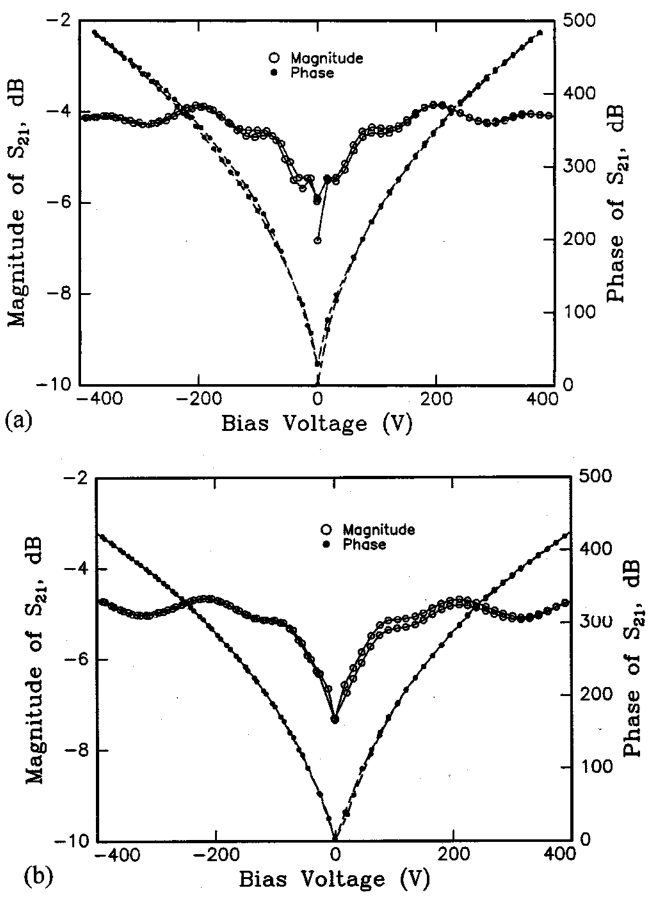


Fig. 11. Eight-element YBCO (350 nm)/STO (1.0 μm)/LAO CMPS. Data were taken at: (a) 40 K and (b) 77 K at a frequency of 16 GHz.

in the odd mode of the RF electric field, is the fundamental building block for the CMPS. Eight such sections are cascaded to obtain the desired phase shift. A biasing network is also shown in the figure to apply bias voltages to each section. By applying a differential dc bias between the coupled lines, one can reach fairly large electric fields between the lines (40 V/μm in Fig. 11) to effectively tune the relative dielectric constant of the ferroelectric thin film. Thus, the coupled microstrips provide more phase shift per unit length (at a specific dc bias) compared to a simple microstrip. However, a CMPS circuit requires careful design as each coupled section is basically a one-pole bandpass filter. The phase shifters were optimized for low insertion loss and maximum relative phase shift. Further information on the phase shifting and passband performance of CMPS circuits has been previously published [24]. Fig. 11 shows the magnitude and phase shift of S_{21} for this circuit using a 1-μm-thick STO film, tested at 40 and 77 K. The phase shift at 40 K is greater because of the large dielectric tunability of STO at this temperature. Between the bias ranges of 75–375 V, a differential phase shift of 290° was observed at 16 GHz, while maintaining the insertion loss below 4.5 dB. This early YBCO prototype device achieved 500° insertion phase shift with 6 dB of loss or a figure-of-merit of about 80°/dB. After much effort, this figure-of-merit has been nearly matched in room-temperature devices employing Au/$Ba_xSr_{1-x}TiO_3$/MgO CMPS devices [25]. It is worth noting that the relative phase shifts increase in direct proportion to the thickness of the ferroelectric thin film. Also, the use of the YBCO electrode instead of gold resulted in higher phase shift for the same thickness of the ferroelectric. This is possibly due to a residual low ϵ layer formed by the oxidized titanium adhesion layer used in the gold-electrode-based circuit. The CMPS discussed here could enable the development of a low-cost easy to fabricate phase-shifter technology with continuous phase-shifting capabilities from 0° to over 360°. Phased-array antennas, particularly reflect arrays, will benefit from this phase-shifter technology.

IV. Summary and Conclusions

In summary, we have demonstrated a new class of low-temperature tunable microwave components based on a CFD two-layered microstrip configuration. The tunable components and circuits we have demonstrated include ring resonators, VCO's, preselect filters, and phase shifters. Tunable Au/STO/LAO ring resonators with unloaded Q as high as 15 000 and frequency tunability factor of over 12% have been demonstrated at 77 K. An Au/STO/LAO-based tunable ring resonator was successfully used as a stabilizing element in a pHEMT-based VCO circuit. The VCO exhibited frequency tunability of over 100 MHz with the ring resonator dc biased at 38 V. Several tunable bandpass filters were demonstrated with tunability factors greater than 9% at or below 77 K, with nondeembedded insertion loss as low as 1.5 dB at K-band frequencies using the YBCO/STO/LAO two-layered microstrip configuration. Also, we have successfully demonstrated continuous differential phase shifts of over 360° at or below 77 K and Ku-band frequencies using coupled microstrip phase shifters. These prototype demonstrations have equaled or exceeded the performance of conventional HTS-based microstrip circuits. The attributes of these components such as small size, light weight, and low loss, as well as their demonstrated performance suggest that they can be used advantageously in satellite communication systems for Ku- and K-band operations.

ACKNOWLEDGMENT

The authors thank SCT, Golden, CO, for the HTS/STO/LAO samples used in this research. The authors also thank N. Varaljay, NASA Glenn Research Center (GRC), Cleveland, OH, B. Viergutz, NASA GRC, Cleveland, OH, and L. McQuaid, NASA GRC, Cleveland, OH, for the patterning and fabrication of the circuits. This work was performed at the NASA GRC.

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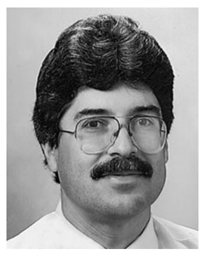

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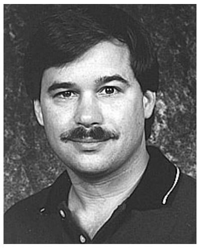

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