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TUNABLE MICROWAVE COMPONENTS FOR Ku- AND K-BAND SATELLITE COMMUNICATIONS

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The use of conductor/ferroelectric/dielectric thin film multilayer structures for frequency and phase agile components at frequencies at and above the Ku-band will be discussed. Among these components are edge coupled filters, microstripline ring resonators, and phase shifters. These structures were implemented using $SrTiO_3$ (STO) ferroelectric thin films, with gold or $YBa_2Cu_3O_{7-\delta}$ (YBCO) high temperature superconducting (HTS) microstrip lines deposited by laser ablation on $LaAlO_3$ (LAO) substrates. The performance of these structures in terms of tunability, operating temperature, frequency, and dc bias will be presented. Because of their small size, light weight, and low loss, these tunable microwave components are being studied very intensely at NASA as well as by the commercial communication industry. An assessment of the progress made so far, and the issues yet to be solved for the successful integration of these components into the aforementioned communication systems will be presented.

Keywords: Ferroelectric thin films; Tunable microwave components; filters; phase shifters; resonators; Ku- and K-band frequencies; satellite communications

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INTRODUCTION

The field of tunable microwave components for communication applications has been traditionally dominated by mechanically tuned resonant structures (e.g., screw-tuned cavity filters), ferrite based components (e.g., ferrite-filled waveguide phase shifters), or semiconductor-based voltage controlled electronics (e.g., FET, PIN-diodes and MMIC based phase shifters and VCOs).[1-3] In recent years, optimization of thin film deposition techniques have enable the growth of high quality ferroelectric thin films (e.g., $SrTiO_3$ and $Ba_xSr_{1-x}TiO_3$) on low loss dielectric substrates such as lanthanum aluminate ($LaAlO_3$) and magnesium oxide (MgO). Values of the relative dielectric constant (ε_r) and dissipation factor (tanδ) of nearly 5000 and 0.005 respectively, have been measured in STO films at 77 K and from 10 KHz to 3 GHz using coplanar capacitors and microstripline resonators.[4,5] Hitherto, the use of conductor/ferroelectric/dielectric (CFD) thin film multilayered structures for microwave components at cellular and PCS frequencies has been hindered because of the rather high values of the ferroelectric film tanδ. However, at higher frequencies (i.e., Ku-band and above) and with the proper circuit geometry and biasing schemes, the impact of tanδ on circuit performance could be greatly diminished. Therefore, these structures could enable the realization of compact, light weight, tunable microwave components critical to NASA's and commercial communications needs at Ku- and K-band frequencies.

In this paper we present results on some proof-of-concept (POC) tunable filters, resonators, and phase shifters. The development stage of these components in terms of their readiness for insertion in actual working systems as well as their advantages with respect to technology currently in use will be discussed.

POC OF TUNABLE COMPONENTS

Tunable Filters

One of the most important components for satellite receiver front end sub-systems is a pre-select filter (usually placed immediately after the antenna element). This filter should feature low insertion loss and sharp out-of-band rejection (i.e., steep roll-off) to provide for a low noise figure and to eliminate band edge spurious effects, respectively.[6,7] Besides these two fundamental characteristics, a filter which can also be tuned in frequency will add great versatility to the receiver since its center frequency can be adjusted so as to pick up the incoming signal at the middle of its passband to enhance performance in a high Doppler environment (LEO satellites), frequency agile systems (MILSTAR), or frequency division multiple access systems (Globalstar). For these filters, tunabilities up to 10% and tuning times of less than 1 ms are desirable. Our group at the Lewis Research Center (LeRC), working in conjunction with the University of Northern Iowa, have developed a proof-of-concept (POC) 2-pole, K-band tunable microwave bandpass filter.[8] Figure 1 shows a schematic of such a filter, while Figs. 2-4 show the modeled and experimental performance, respectively, for the filter implemented using a $YBa_2Cu_3O_{7-d}$ (YBCO)/STO/ $LaAlO_3$ (LAO) CFD multilayered structure. The modeled filter (shown in Figure 2) exhibits a minimum insertion loss of 0.7 dB, which barely changed with ε_r values from 300 to 3000. Also, the center frequency of the filter changed from 17.75 GHz for ε_r=3000 to 20.75 GHz for ε_r=300 (i.e., 14% tunability). For all cases, the return losses were better than 20 dB. Experimentally, the passband of the filter changed by 1.7 GHz at 77 K and by more than 2 GHz at 24 K, with the filter passband and bandwidth improving with increasing bias. (see Figures 3 and 4). At 24 K, the filter exhibits non-deembedded insertion losses of nearly 1.5 dB (~ a factor of 3 of the modeled result). By the "non-deembedded" term

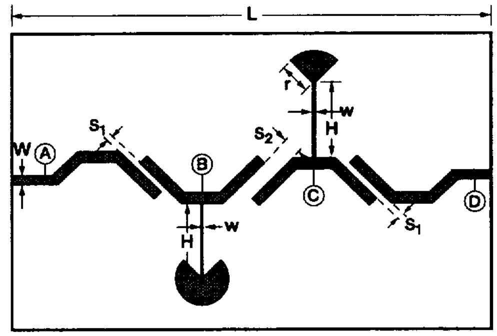

FIGURE 1 Schematic of a tunable bandpass filter ciruit. The dimensions are: W = 86.25 μm, L = 6.8 mm, S_1 = 100 μm, S_2 = 300 μm, H = 1.33 mm, w = 12.5 μm, and r = 200 μm.

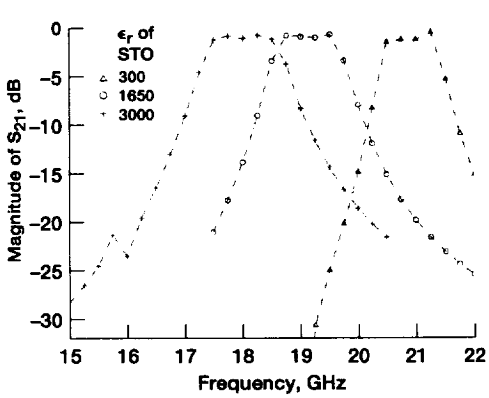

FIGURE 2 Modeled data for the bandpass filter generated using Sonnet em® simulator.

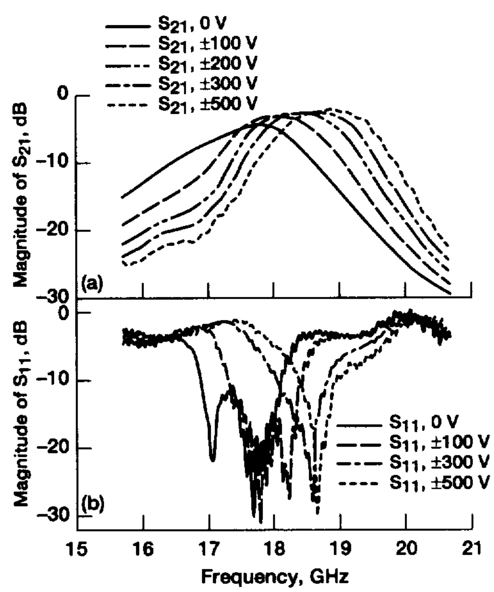

FIGURE 3 Field dependence of S_{21} and S_{11} for the YBCO/STO/LAO bandpass filter at 77 K.

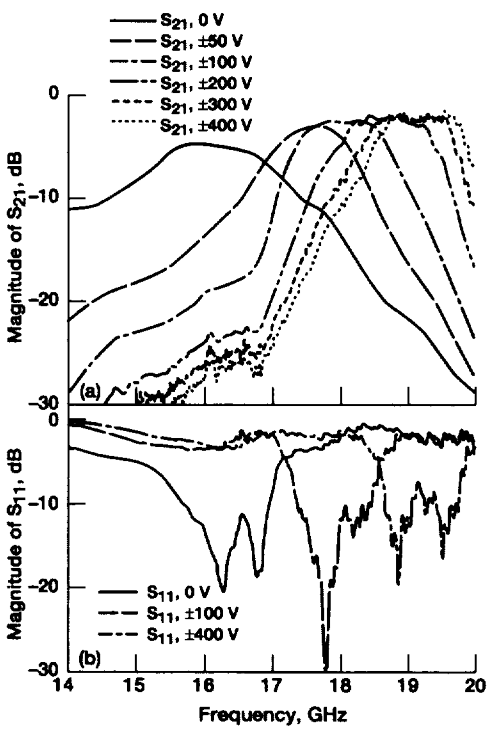

FIGURE 4 Field dependence of S_{21} and S_{11} for the YBCO/STO/LAO bandpass filter at 24 K.

we imply that the data reported are the "raw" data, and no corrections for the losses introduced by the SMA launchers, whose effect were not accounted for during calibration, have been made. The type of filters discussed here are designed to operate under bias rather than at zero volts. At cryogenic temperatures, both the ε_r and $\tan\delta$ of STO films approach their highest value. By applying bias, both ε_r and $\tan\delta$ decrease resulting in frequency tuning of the filter and lower insertion losses, respectively, as well as more optimized passband and bandwidth due to better matching. Thus, it is reasonable to assess the quality of the filter under the most optimized conditions, i.e., under bias, instead of at zero volts dc. Using the expression for the figure of merit, K, of tunable filters as defined by Vendik, et al.[9],

$$K = 2Q\Delta f/f \qquad (1)$$

where Δf is the tunable bandwidth, f is the frequency of operation, and Q is the unloaded quality factor, gives K = 34 for this filter at 24 K. Note that this calculation ignores the zero bias state because the filter is not designed to operate at zero bias. To illustrate the impact of these results for a typical communication link, let us consider a LEO-to-ground link at 19 GHz. We assume an antenna efficiency of 60% and an antenna noise temperature of 50 K. Furthermore, it is also assumed that the antenna and a feed with a loss of 0.5 dB are kept at 290 K which is the most probable scenario. Finally, we assume a low noise amplifier with a gain of 23 dB and a noise figure of 1 dB (e.g., pHEMT LNA). Shown in Table I is the effect of bandpass filter insertion loss (I.L.) on system noise temperature and normalized antenna size.

TABLE I Effect of Filter Insertion Loss on Receiver Front End Parameters

Filter Insertion Loss (dB)	System Noise Temperature (K)	Noise Figure (dB)	Normalized Antenna Area
0.5	319	3.2	1.0
1.5	439	4.0	1.4
3.0	679	5.2	2.1

In addition, the attributes of this filter configuration of ease of fabrication (single stage photo-lithography), small size (6.8 mm × 3 mm), and planar geometry (i.e., ease of insertion into MMIC systems) make this type of filter technology very appealing for insertion into satellite receiver front ends.

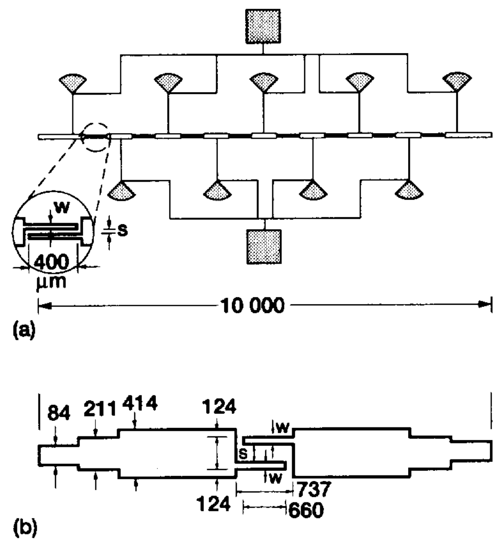

FIGURE 5 (a) Schematic of eight-elements, 50 Ω CMPS. S = 7.5 µm and W = 25 µm. (b) Schematic of 25 Ω single-element CMPS. S = 12.7 µm and W = 76.2 µm. All other dimensions are in microns.

<u>Coupled Microstripline Phase Shifters</u>

Another area of application of the technology under discussion is in the fabrication of compact, low loss phase shifters. In general, phase shifting elements can be realized through the use of ferrite materials, MMICs, and diodes (e.g., switched line, reflection and loaded line). Typically, diode or MESFET phase shifters are digital with bits of 11.25, 22.5, 45, 90, and 180 degrees. Losses increase with the number of bits (~2 dB/bit), and the discrete phase shift steps sometimes result in scanning granularity. Unfortunately, MMIC technology has not yet lived up to its promise of low cost for phased array applications. Despite the cost, MMICs remain the technology of choice for K-band and above phased arrays. Therefore, development of a low cost and reliable alternate solution is desirable. At LeRC, we have demonstrated that the CFD thin film multilayered structures could enable the development of a low cost, easy to fabricate, phase shifter technology with continuous phase shifting capabilities from zero to over 360 degrees.[10]

Figure 5(a) shows a schematic of an eight-element, K-band coupled microstripline phase shifter (CMPS) fabricated with a YBCO (0.35 µm thick)/ STO (1.0 µm thick)/LAO (254 µm thick) CFD multilayered structure. As shown in Fig. 6, this configuration allows for insertion phase shifts of more than 400 degrees at dc voltages of 400 V, 77 K, and 16 GHz, with nominal losses below 6 dB. Details of this CMPS are discussed by Van Keuls, et al. in a parallel paper presented at this conference.[11] Because of the use of STO this phase shifter has been demonstrated at cryogenic temperatures. However, room temperature performance can be attained replacing the STO by $Ba_xSr_{1-x}TiO_3$ (BSTO) as shown in Fig. 7 for the single-element, 25 Ω CMPS, shown in Fig. 5(b). Phase array antennas, particularly reflectarrays, will benefit from the phase shifter technology described herein. Schematics of competing antenna

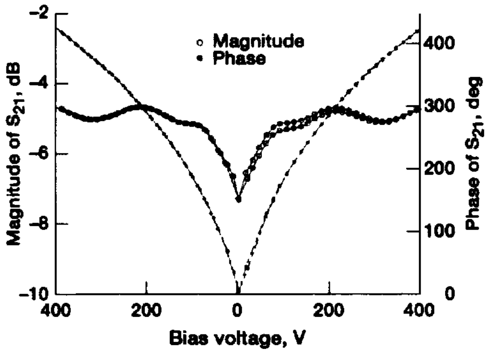

FIGURE 6 50 Ω, eight elements YBCO (350 nm)/ STO (1.0 μm)/LAO CMPS. Data were taken at 77 K and 16 GHz.

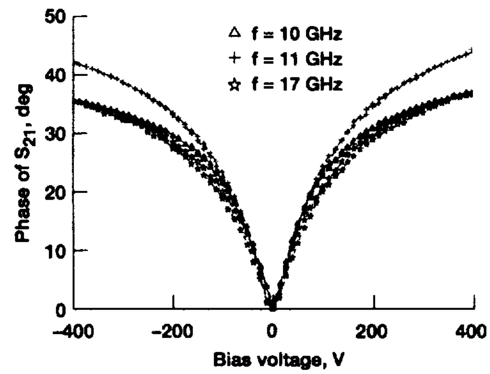

FIGURE 7 25 Ω, single element Au (2.5 μm)/ BSTO (300 nm)/LAO CMPS. Ba:Sr ratio is 60:40. Data were taken at 300 K.

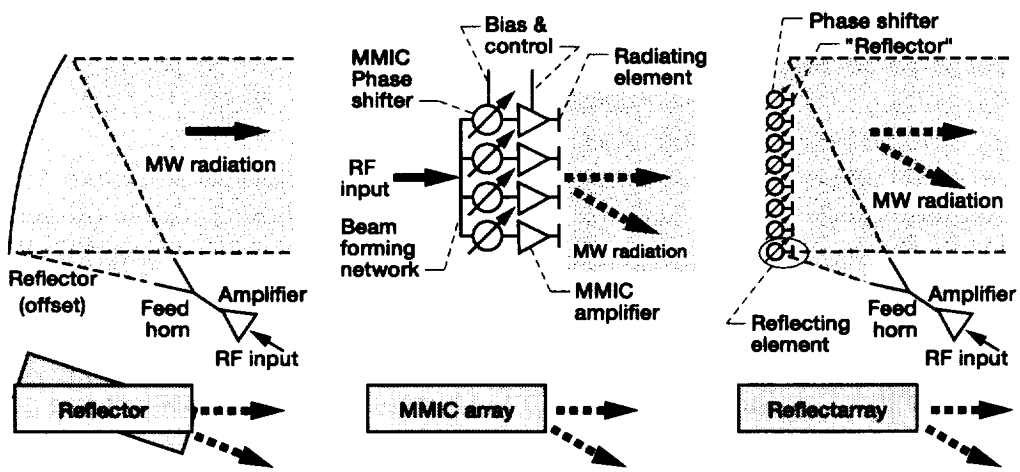

FIGURE 8 Schematic of competing antenna technologies for satellite communications.

TABLE II Comparison Between Main Antenna Technologies For Satellite Communications.

Gimbaled Parabolic Reflector	MMIC Direct Radiating Array	Reflectarray
Simple Configuration	Beam Forming Manifold	Space Fed (no Manifold)
Mechanical Beam Steering	Electronic Steering	Electronic Steering
Low Cost:~$100 K	High Cost:~$ 1000 K	Low Cost:<$ 100 K
Overall Efficiency: ~ 55%	efficiency: ~ 20%	efficiency: ~25 %
Multiple Single Point Failure	Graceful Degradation	Single Point Failure
	Thermal Management Issues	Larger Aperture
	Compact/Low Profile	Compact/Low Profile

technologies for satellite communications are shown in Fig. 8 and a comparison among them is shown in Table II.

Traditionally, gimbaled configurations are used because of low cost and high efficiency. When fast and vibration free scanning is required one generally invests in the MMIC approach, which is the current situation confronting NASA, and thus prompting investigation of the reflectarray approach. There are speculations that eventually the cost per element of MMIC arrays will approach $100.00 for large production volumes. Likewise, the cost of high volume production of the reflectarray should also track this trend.

Tunable ring resonators

Microstrip ring resonators are widely used in microwave electronics both as material characterization tools, as well as critical components of high frequency devices such as ring resonator filters and stabilizing elements in local oscillators.[12,13] At LeRC we have investigated the performance of interdigital and contiguous ring resonators using Au/STO/LAO and YBCO/STO/LAO CFD structures. Figure 9 shows the schematic and the results for a YBCO (0.35 nm)/ STO(300 nm)/LAO (254 μm) 25 Ω, 2λ interdigital ring resonator at 10 GHz. At 77 K, a 110 MHz frequency shift was obtained applying a 160 V dc to the upper half of the resonator while grounding its lower half and the transmission line. A 160 MHz shift was obtained at 50 K under the same bias conditions. We also have developed 2πR=3λ contiguous ring resonators at K-band frequencies

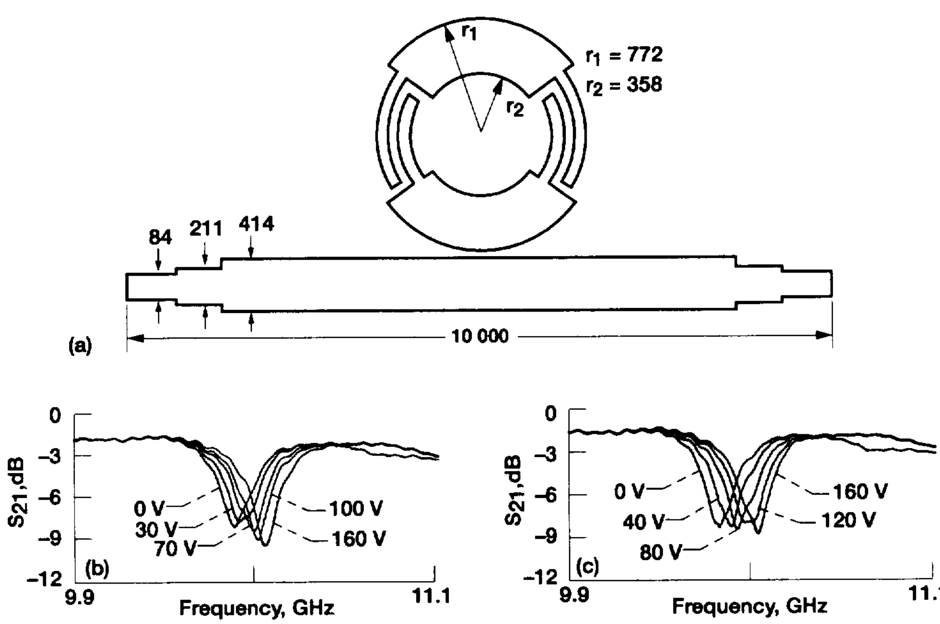

FIGURE 9 (a) 25 Ω ring resonator with interdigital gaps and input/output 50 to 25 Ω transformer. All dimensions are in microns. Performance of a YBCO (350 nm)/STO (300 nm)/LAO (254 μm) ring resonator at 77 K (b) and 50 K (c).

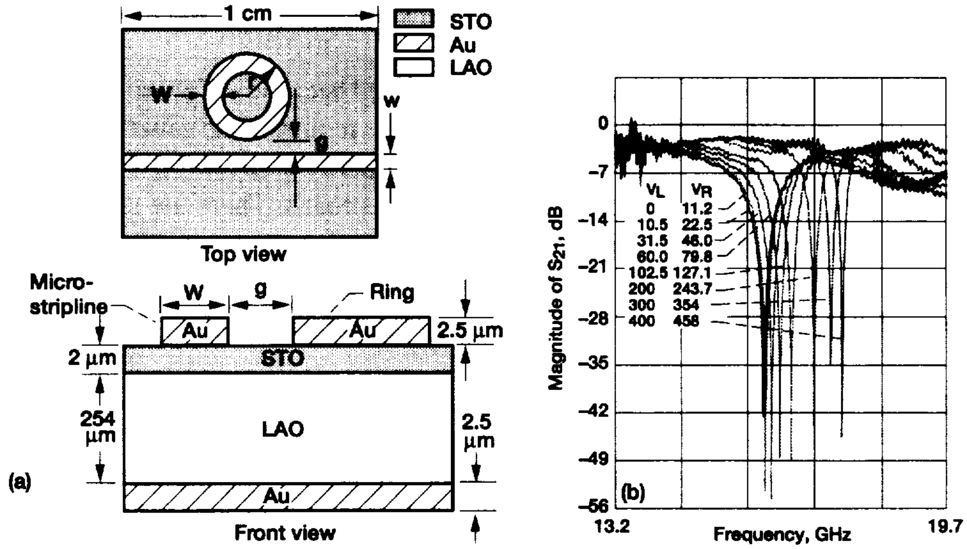

FIGURE 10 (a) Microstripline side-coupled, 25 Ω ring resonator. W = 406 µm, w = 89 µm, r = 1694 µm, and g = 25 µm. (b) Effect of dc bias on the 3 λ resonant frequency and resonance sharpness factor of the Au/STO/LAO ring resonator at 77 K and for the ring and line voltage values (V_R and V_L, respectively) shown in the figure.

(see Fig. 10(a)).[14] Figure 10(b) shows data for one of these "bandstop" Au (2.5 µm)/STO(2 µm)/LAO (254 µm) 25 Ω resonators. Among the data shown in Fig. 10(b), are resonances with sharpness ($f_o/\Delta f_{3dB}$)* as high as 12,000. For the bias range indicated in the figure, the 3λ resonance of the ring was tuned from 15.75 to 17.41 GHz while keeping $f_o/\Delta f_{3dB}$ above 768 within the whole range. Based on a lumped element equivalent circuit model we have estimated the unloaded Q (Q_o) of this circuit to be near 750. As such, they compare favorably with those reported at Ka-band for gold microstrip resonators on GaAs substrates (e.g., Q_o=271 at 77 K and 31 GHz),[15] and also for copper microstipline resonators on teflon (e.g., Q_o=500 at 15 GHz and room temperature).[16] However, they are lower than those reported for dielectric resonator oscillators (DROs) for which Q_o~50,000 at 10 GHz have been reported.[17] Nevertheless, DRO's manufacturing cost, lack of electronic tunability, and non-planar geometry limits their versatility for insertion in frequency agile systems such as tunable local oscillators and broadband bandstop filters. The evaluation of the insertion of CFD ring resonator technology on working systems is currently underway. For example, Romanofsky, et al.,[18] have used a CFD of ring resonator to develop a Ku-band tunable local oscillator for satellite communications. It is also conceivable that CFD ring resonator technology will be used successfully for the development of notch filters for wireless communications.[19]

*f_o is the resonant frequency and Δf_{3dB} is the frequency width at 3dB up from the power level at f_o.

CONCLUSIONS

We have described several POC of Ku- and K-band, tunable microwave components fabricated using (gold,YBCO)/STO/LAO conductor/ferroelectric/ dielectric thin film multilayer structures. The attributes of these components of small size, light weight, and low loss, as well as their demonstrated performance, suggest that they can be used advantageously, even at the current level of development, in satellite and wireless communication systems for Ku- and K-band operation. In the mean time, further optimization of BSTO ferrroelectric thin films should enable the realization of low cost frequency agile technology for room temperature applications.

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13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS

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