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INFLUENCE OF THE BIASING SCHEME ON THE PERFORMANCE OF Au/SrTiO₃/LaAlO₃ THIN FILM CONDUCTOR/FERROELECTRIC TUNABLE RING RESONATORS

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The performance of gold/SrTiO₃/LaAlO₃ conductor/ferroelectric/dielectric side-coupled, tunable ring resonators at Ku-band frequencies is presented. The tunability of these rings arises from the sensitivity of the relative dielectric constant (ϵ_r) of SrTiO₃ to changes in temperature and dc electric fields (E). We observed that the change in ϵ_r which takes place by biasing the ring up to 450 V alters the effective dielectric constant (ϵ_{eff}) of the circuit resulting in a 3λ resonant frequency shift of nearly 12% at 77 K. By applying a separate dc bias between the microstrip line and the ring, one can optimize their coupling to obtain high Q bandstop resonators with $\delta f_n^{-1} = f_o/\Delta f_{3\text{dB}}$ as high as 12,000. The 3λ resonance was tuned from 15.75 to 17.41 GHz while keeping δf_n^{-1} above 768 over this range. The relevance of these results for practical microwave components will be discussed.

Keywords: Tunable Ring Resonators; Ku-band frequencies; Ferroelectric thin films; biasing scheme; quality factor.

INTRODUCTION

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 stabilizing elements in local oscillators.^[1-5] The unloaded quality

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factor (Q_0) of a ring resonator is closely related to the microwave properties of the materials forming this resonant circuit as shown by the following expression:[4]

$$Q_0 = \pi / \alpha \lambda_g = (\pi f \sqrt{\epsilon_{\text{eff}}}) / c \alpha \quad (1)$$

where α is the attenuation coefficient of the transmission line, λ_g is the guide wavelength, c is the speed of light, f is the frequency, and ϵ_{eff} is the effective dielectric constant of the circuit. Because of its geometry, and under appropriate shielding, the radiation losses for a ring resonator are small. Therefore, most of the time α will be the sum of the attenuation due to the conductor (α_c) and that of the dielectric substrate (α_d) of the ring. However, the contribution to the overall value of α arising from dielectric losses can be greatly diminished by using substrates such as lanthanum aluminate (LaAlO_3), magnesium oxide (MgO), and sapphire (Al_2O_3), which exhibit very low losses (i.e., $\tan\delta < 10^{-5}$). Thus, for most applications, the Q_0 of ring resonator is limited by conductor losses. This problem has been addressed to a great extent by using High Temperature Superconducting (HTS) thin films (e.g., $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$) as the conducting layers in these circuits. Because of their low surface resistance, HTS-based ring resonators, with Q_0 's orders of magnitude higher than their normal conductor counterparts, have been demonstrated.[6]

Despite these advances, there are still concerns regarding the discrepancies between the modeled parameters (e.g., resonant frequency and Q_0 values) and those obtained after fabrication and testing of the circuit. In addition, even when close agreement between the simulated and actual experimental performance of a device is attained, its predetermined frequency of operation diminishes its versatility for applications in frequency agile components such as tunable local oscillators and tunable narrow-band bandstop filters, among others. Therefore, a simple and cost effective way to address these deficiencies is required.

Recently, the use of SrTiO_3 (STO) and $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$ (BSTO) thin ferroelectric films in conductor/ferroelectric/dielectric multilayered structures have enabled the successful demonstration of tunable microwave components such as phase shifters and filters.[7,8] Still, the rapid optimization and commercialization of this type of components have been hindered by the high losses exhibited by the ferroelectric films with respect to that of typically used microwave substrates such as those mentioned above. Therefore, we have endeavored to find circuit configurations where the effect of these losses on circuit performance can be diminished through the versatility gained by tuning the relative dielectric constant (ϵ_r) of the ferroelectric.

In this paper, we report on the performance of gold/ SrTiO_3 / LaAlO_3 (Au/STO/LAO) side-coupled ring resonators at Ku-band frequencies using several

biasing schemes. Because of the sensitivity of the dielectric constant of the STO film (ϵ_{rSTO}) to variations in dc electric fields (E) at temperatures below 100 K,^[9] biasing the ring results in tuning its resonant frequency (f_0) by as much as 12 percent. Further, by applying a separate bias between the microstrip transmission line and the ring one can optimize their coupling to obtain high $\delta f_n^{-1} = f_0/\Delta f_{3\text{dB}}$ resonances. Also, by changing both of these voltages in a correlated way these sharp resonances can be tuned over a frequency range larger than 1 GHz. The implication of these results for practical microwave applications will be discussed.

EXPERIMENTAL

The ring resonators discussed in this study were fabricated in our laboratory using laser ablated STO thin films of different thickness (0.3–2.0 μm thick) on LAO substrates (254 μm thick). These films were obtained from Superconducting Core Technologies (SCT), Golden, CO. The samples were coated on both sides with a 15 nm thick titanium adhesion layer followed by a 2.5 μm thick gold film using electron beam evaporation. The ring was designed so as to satisfy the condition $2\pi R = 3\lambda$, where R is the mean radius of the ring, at $f_0 = 20$ GHz and no STO (see Fig. 1(a)). The 3λ resonance was chosen to satisfy R (i.e., the mean radius of the ring) being significantly larger than W (i.e., the line width of the ring), in order to avoid moding problems. Selection of the fundamental would have caused the ring to essentially degenerate into a disk. The presence of the STO film will lower the resonant frequency depending upon its dielectric constant (ϵ_{rSTO}) and its thickness. It has been shown that for the STO thin films used in this study ϵ_{rSTO} varies nonlinearly from 300 at room temperature to values up to 3500 at

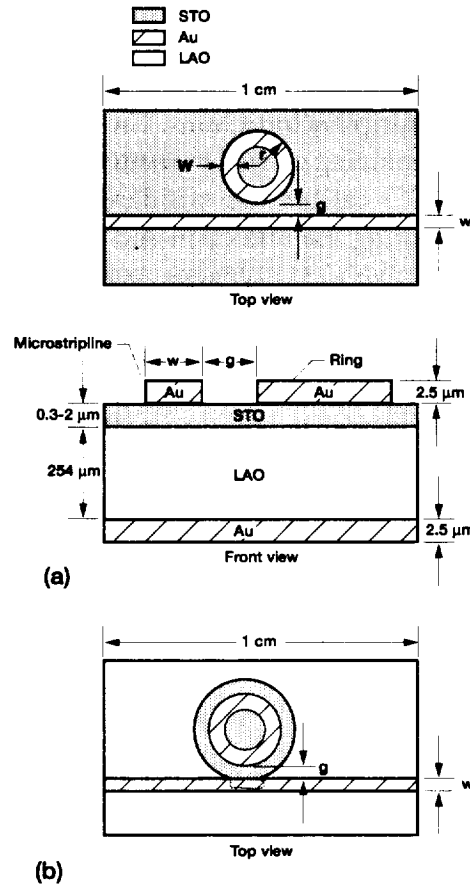


FIGURE 1 Microstripline side-coupled ring resonator. $W = 406 \mu\text{m}$ for the 25 Ω ring and $89 \mu\text{m}$ for the 50 Ω ring. $w = 89 \mu\text{m}$ and $g = 25 \mu\text{m}$, $r = 1694 \mu\text{m}$.

temperatures below 80 K.^[9] Also, at cryogenic temperatures, ϵ_{rSTO} values can approach those at room temperature by applying a dc bias. Therefore, the ϵ_{rSTO} value used for the ring resonator design, enables tuning to lower (higher) resonant frequencies by decreasing (increasing) the magnitude of the dc bias applied to the ring. Patterning of the ring was performed using standard photolithography and lift-off chemical etching techniques. For some of the rings, the STO layer was left undisturbed before patterning the ring (i.e., STO covering all the surface of the LAO substrate) as shown in Fig. 1(a). For others, the STO was etched away using a 7% solution of hydrofluoric (HF) acid except in the areas right underneath the ring and the coupling gap between the ring and the microstrip transmission line, as shown in Fig. 1(b). Similar Au/LAO resonators were also patterned for comparison purposes.

Microwave testing of the resonators was performed by mounting the resonator on a brass test block customized to fit on top of the cold finger of a closed-cycle helium gas refrigerator. Semirigid coaxial cables were used as waveguides for the microwave signal from an HP 8510-C Automatic Network Analyzer (ANA) to the sample. SMA launchers were used at the input and output coaxial-to-microstripline transitions. The system was calibrated at room temperature before the beginning of each measurement cycle using coaxial short-open-load-through (SOLT) calibration standards. The ring resonators were characterized by measuring the reflection and transmission scattering parameters (S_{11} and S_{21} , respectively) at cryogenic temperatures and under dc voltages (V_{dc}) from zero to 450 dc volts. The dc bias was applied to the ring through 0.7 mil Au wires attached to it using a thermal wire-bonding method. The wire was bonded to the ring at a virtual short circuit position, nearly opposite of the coupling gap, so as not to perturb the resonance. Bias to the microstrip transmission line was applied through the SMA launchers using custom made bias “tees” that allow the application of up to 500 V_{dc} at K-band frequencies^[10]. Data were taken using each of the three biasing schemes illustrated in Fig. 2. Results of these measurements will be discussed in the next section.

RESULTS

Two side-coupled ring resonator designs, with 50- Ω and 25- Ω characteristic impedance at room temperature* were tested with several STO film thickness. Data for each of these rings are summarized in Table I. The δf_n^{-1} values measure the sharpness at resonance and are defined as $\delta f_n^{-1} = f_o / \Delta f_{3\text{dB}}$, where $\Delta f_{3\text{dB}}$ is the measured width at 3 dB above the resonance level. For most systems, this

*Since variations in ϵ_{rSTO} change the impedance with changing temperature and dc bias.

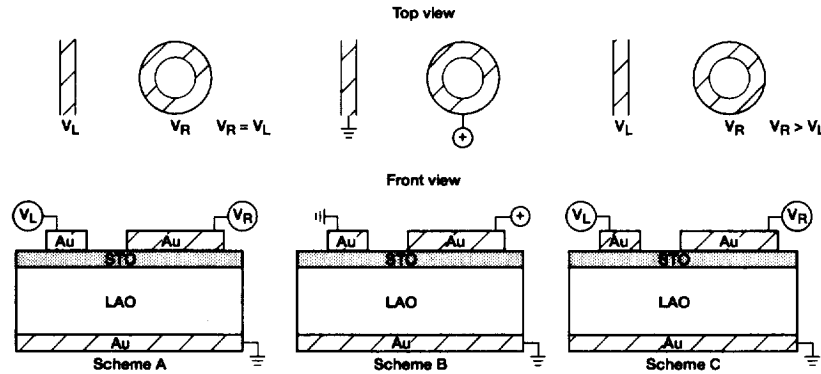


FIGURE 2 Biasing schemes used to test the tunable ring resonators: scheme A (ring and line at the same potential, $V_R = V_L$); scheme B (ring biased, line grounded); scheme C (ring biased at V_R and line at V_L , where $V_R > V_L$).

TABLE I Maximum δf_n^{-1} and Frequency Tuning Range of Au/SrTiO₃/LaAlO₃ Ring Resonators Versus Temperature and Bias

| Sample number | Design and STO thickness | T (K) | Maximum V_R (V) | $3\lambda_g$ Resonance frequency range (GHz) | Maximum δf_n^{-1} |
|---------------|---|-------|-------------------|--|---------------------------|
| 1 | Au 50 Ω ring, 300 nm | 40 | 300 | 14.6 - 16.2 | 89 |
| 1 | “ “ | 77 | 350 | 15.1 - 16.8 | 38 |
| 2 | Au 25 Ω ring, no STO | 40 | na | 20.48 | 652 |
| 2 | “ “ | 77 | na | 20.47 | 560 |
| 3 | Au 25 Ω ring, 300 nm | 40 | 450 | 19.0 - 20.0 | 553 |
| 3 | “ “ | 77 | 350 | 19.3 - 19.9 | 344 |
| 4 | Au 25 Ω ring, 1 μm | 52 | 250 | 17.0 - 18.1 | 150 |
| 5 | Au 25 Ω ring, 2 μm | 77 | 458 | 15.75 - 17.64 | 12,000 |
| 6 | Au 25 Ω ring, 2 μm partially etched | 77 | 491 | 15.27 - 17.26 | 15,000 |

measurement would equal the unloaded quality factor (Q_0) even after accounting for corrections due to loading effects using the method of Khanna and Garault.^[11] However, because of the ferroelectric film, our measurement of S_{21} includes both variable coupling loss and the effects of the microstrip between the reference plane of the ring and the sample edge, whose loss and impedance also change with bias. Also, these are two coupling modes (i.e., even and odd) whose relative strengths change with tuning the circuit. These effects alter the usual Q_0 calculation in a complicated manner and will be explored in a later publication. The actual value of Q_0 is believed to be limited to ~ 750 in these rings, based on a lumped element equivalent circuit model. This value was calculated assuming a resistivity for gold of $0.15 \mu\Omega\text{-cm}$ (which is a conservative value for bulk gold at 77 K). The S_{21} resonances of samples 1-4 in Table I correspond to an under-coupled state of the ring resonance. Maximum coupling to the ring was obtained

under biasing scheme A (see Fig. 2). In this configuration there is a field only between the resonant circuit and the ground plane, with most of the E field concentrated in the LAO substrate, and therefore ϵ_{rSTO} between the ring and the line nears its highest possible value at the particular cryogenic temperature under consideration. Contrary to samples 1-4, we observed that for the same bias scheme, sample 5 of Table I was over-coupled. The performance of this Au/STO/LAO ring resonator under this biasing scheme and at 77 K is shown in Fig. 3. Note that for all the bias values shown, the δf_n^{-1} 's are low and decrease with increasing bias. However, for the maximum bias shown (i.e., 350 V), a shift in f_0 of nearly 1 GHz is attained. For this sample the coupling state of the resonator can be changed from over-coupled to under-coupled by applying a dc bias between the ring and the microstrip transmission line, reducing the value of ϵ_{rSTO} within the gap. Figure 4 illustrates the effect of holding the line voltage (V_L) at 0 V_{dc} while varying that of the ring (V_R) through several values of V_{dc}. At $V_R=0$, the 3λ S_{21} resonance is over-coupled. Increasing V_R up to 13.65 V, shifts f_0 upward by ~100 MHz and increases δf_n^{-1} . Although the shift of f_0 to higher frequencies continues as V_R is increased further, the δf_n^{-1} values and the degree of coupling decrease to the extent that for $V_R \geq 30$ V the ring becomes under-coupled and exhibits a small δf_n^{-1} .

So far we have seen that biasing schemes A and B offer rather limited advantages for practical insertion into working systems. That is, for a similar bias range, scheme A allows for large frequency tunability but the δf_n^{-1} values are low and decrease even more with bias. On the contrary, it is feasible to attain large δf_n^{-1} 's with small voltages under biasing scheme B. However, a suitable δf_n^{-1} value occurs only at a single frequency, and drops dramatically just tens of

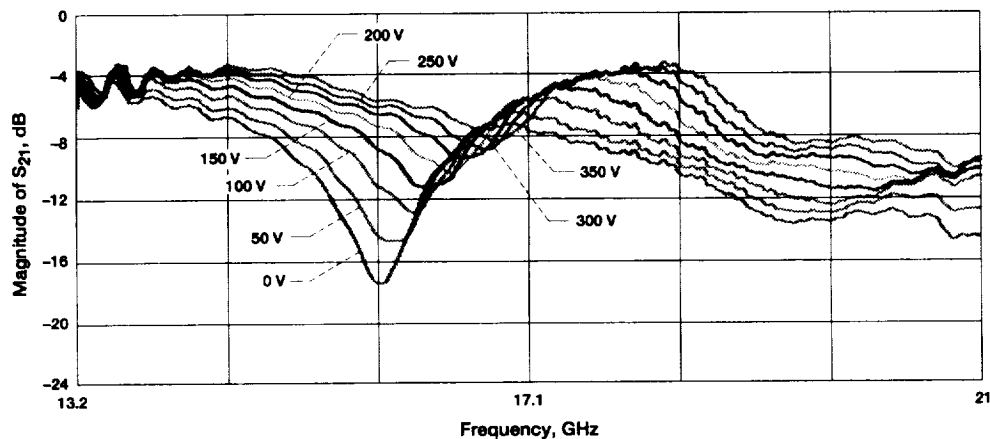


FIGURE 3 Effect of dc bias on the 3λ resonant frequency (f_0) and sharpness of resonance δf_n^{-1} of the Au/STO/LAO ring resonator (#5 of Table I) at 77 K and under bias scheme A.

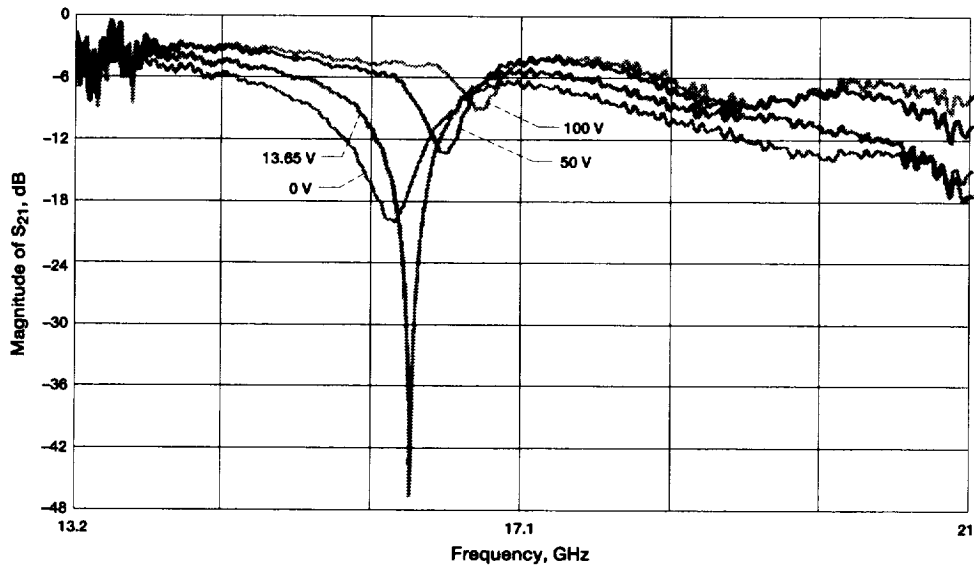


FIGURE 4 Effect of dc bias on the 3λ resonant frequency (f_0) and sharpness of resonance δf_n^{-1} of the Au/STO/LAO ring resonator (#5 of Table I) at 77 K and under bias scheme B.

MHz below and above such a frequency. That is, there is just an optimal voltage value, and therefore a single frequency, at which a practical δf_n^{-1} value can be attained eradicating all the intended advantages of tunability.

We have observed that the high δf_n^{-1} values as well as the broad tuning range of the resonator can be maintained by adjusting V_L and V_R in a correlated way. That is, using biasing scheme C of Fig. 2, one can optimize the coupling and sharpen the 3λ resonance while maintaining large tunabilities. The magnitude of S_{21} resulting from this differential biasing scheme is shown in Fig. 5. Note that as V_R grows, the optimal difference $\Delta V = V_R - V_L$ also increases mainly due to the nonlinearity of $\epsilon_{r\text{STO}}$. The data shown in Fig. 5, exhibit bandstop ring resonators with δf_n^{-1} 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 δf_n^{-1} above 768 within the whole range.

Note that similar results can also be attained for the configuration shown in Fig. 1(b) using biasing scheme C, as shown in Fig. 6. This configuration and biasing scheme could be the most desirable one for practical microwave applications since it place the tuning element (i.e., the ferroelectric film) only underneath the coupling sections of the circuit freeing the remaining area of the chip for additional non-tunable circuitry. The highest δf_n^{-1} of 15,000 measured for this configuration under biasing scheme C compares favorably with Q_0 values reported at Ka-band for gold microstrip resonators on GaAs substrates (e.g., $Q_0=271$ at 77 K and 31 GHz),^[12] and also for copper microstripline resonators

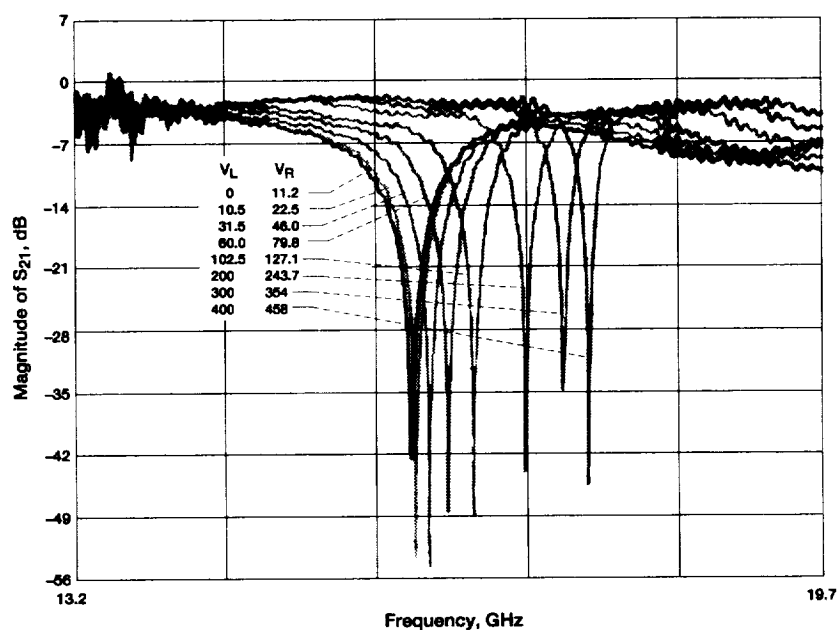


FIGURE 5 Effect of dc bias on the 3λ resonant frequency (f_0) and sharpness of resonance δf_n^{-1} of the Au/STO/LAO ring resonator (#5 of Table I) at 77 K and under bias scheme C.

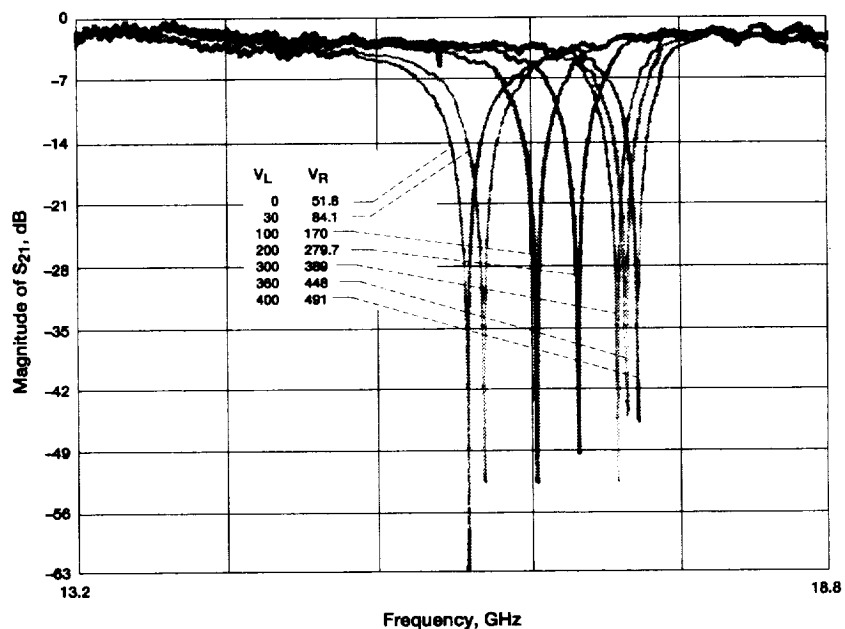


FIGURE 6 Effect of dc bias on the 3λ resonant frequency (f_0) and sharpness of resonance δf_n^{-1} of the partially etched Au/STO/LAO ring resonator (#6 of Table I) at 77 K and under bias scheme C.

on teflon (e.g., $Q_0=500$ at 15 GHz and room temperature).^[13] Although Q_0 values near 50,000 at 10 GHz have been reported for dielectric resonator oscillators (DROs)^[14], their 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 tunable narrow-band bandstop filters.

CONCLUSIONS

The performance of gold/SrTiO₃/LaAlO₃ conductor/ferroelectric/dielectric side-coupled, tunable ring resonators at K-band frequencies and under different biasing schemes has been discussed. We observed that the change in the dielectric constant of the SrTiO₃ which takes place by biasing the circuit affects the δf_n^{-1} values and the resonant frequency of the circuit in different ways depending on the biasing scheme used. The best performance of these resonators was obtained by applying a separate dc bias between the microstrip line and the ring. The optimized coupling resulted in bandstop resonators with δf_n^{-1} as high as 15,000. Under this biasing scheme the 3λ resonance was tuned from 15.75 to 17.41 GHz while keeping δf_n^{-1} above 768 over this range. These δf_n^{-1} values and tuning ranges feature the advantages of these tunable circuits as a potential technology of choice for tunable local oscillators, tunable narrow-band bandstop filters, and other practical microwave applications requiring low cost and reliable frequency agile capabilities.

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