Chapter

Tunable Zeroth-Order Resonator Based on Ferroelectric Materials

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Abstract

Tunable microwave devices have the benefits of added functionality, smaller form factor, lower cost, and lightweight, and are in great demand for future communications and radar applications as they can extend the operation over a wide dynamic range. Current tunable technologies include several schemes such as ferrites, semiconductors, microelectromechanical systems (MEMS), and ferroelectric thin films. While each technology has its own pros and cons, ferroelectric thin film-based technology has proved itself as the potential candidate for tunable devices due to its simple processes, low power consumption, high power handling, small size, and fast tuning. A tunable Composite Right Left-Handed Zeroth Order Resonator (CRLH ZOR) is introduced in this chapter and it relies mainly on the latest advancement in the ferroelectric materials. It is common that for achieving optimum performance for the resonant structure, this involves the incorporation of an additional tuning by either mechanical means (i.e. with tuning screws) or other coupling mechanisms. The integration between electronic tuning and High-Temperature Superconducting (HTS) components yields a high system performance without degradation of efficiency. This leads not only low-loss microwave components that could be fine-tuned for maximum efficiency but will provide a tunable device over a broadband frequency spectrum as well. The dielectric properties of the ferroelectric thin film, and the thickness of the ferroelectric film, play a fundamental role in the frequency or phase tunability and the overall insertion loss of the circuit. The key advantages of using ferroelectric are the potential for significant size-reduction of the microwave components and systems and the cabibility for integration with microelectronic circuits due to the utilization of thin and thick ferroelectric film technology. In this chapter, ZOR is discussed and the conceptual operation is introduced. The ZOR is designed and simulated by the full-wave analysis software. The response is studied using electromagnetic characteristics with the applied electric field, ferroelectric thickness, and the operating temperature.

Keywords: HTS, Ferroelectric, Superconductor, Tunability, Zeroth-order Resonator (ZOR)

1. Introduction

Microwave devices that can be electronically tuned and switched are indispensable components for more complex and versatile communication systems. Tunable devices add new functionality and make it possible to design communication systems of reduced size and complexity. A single tunable filter, for instance, can replace a complete filter bank consisting of multiple filters. Tunable antennas arranged as an array (phase array systems) will work together as a beam antenna with beam orientation and beam angle that are electronically adjustable. Using tunable phase-shifters for separate phase-control of each antenna feed signal can accomplish this. Tunable impedance matching networks are other critical examples of devices that are required to compensate for regular and rapid changes in the radiation resistance of portable systems (e.g., cell phones).

Several technologies of providing tunability have been proposed in the literature. Tunable devices can, for example, deploy varactors and switches based on semiconductors, optical elements, liquid crystals, magnetic materials, ferroelectric materials, or microelectromechanical systems (MEMS). In terms of achievable tunability, loss contribution, linearity, tuning speed (switching rate), bias voltage, power consumption, microwave power handling capability, cross-sensitivity (temperature dependence, vibration, etc.), reliability, life cycle, area consumption, manufacturing compatibility (especially CMOS compatibility), and manufacturing cost, these approaches may differ. Therefore, the appropriate choice of the tuning method may rely on the specific application, where tunability is needed.

Each tuning mechanisms have merits and demeitrs. For instance, the magnetic and optical tuning are contactless, i.e., they do not require DC biasing network. Therefore they do not cause extra parasitics in the circuit. However, both of these methods employs a high control power. Additionally the tuning topology based on MEMS, semiconductor, etc., require DC biasing networks, which leads to wiring connection problems. The tunable metamaterials consisting of large numbers of unit cells and this causes complex wiring syste and power distribution bottleneck of the network. MEMS tuning method has additional disadvantages of being slow and requiring vacuum packaging. On the other hand, ferroelectrics have extremely low leakage currents less than MEMS counterparts. A comparison of the available tuning methods [1] shows that the ferroelectric tuning method is best suited for tunable metamaterial applications.

2. Ferroelectric tunable microwave components

Since the early 1960s, ferroelectrics have been explored for application in microwave devices and radar applications [2–5]. Their characteristics have been extensively recognized by several research groups around the world. However, their applications are starting to emerge recently [6–14]. This recent resurgent interest is due to a number of factors, such as their final application compatibility with high-temperature superconductors and similar production methods. The key to a broad variety of applications is the change in permittivity as a function of the electric field.

Frequency-agile resonators are considered a potential applications out of many devices of ferroelectrics. Such components can find a wide range of applications in several communications, industrial, commercial, and radar systems. Frequency tunability in microwave circuits can be realized using ferroelectric thin films incorporated into conventional microstrip circuits. Electronically tunable resonators can be produced with applications of interference suppression, secure communications, dynamic channel allocation, signal jamming, and ground-based communications switching. Many new systems concepts will developed as high-performance materials emerge; these systems will have considerably improved performance over conventional systems.

Ferroelectric tunable resonators have reliable perfromance, small footprint, and lightweight because they depend on electric fields and have low power consumption. The tunability factor is quite large, and devices are relatively simple in nature. The main problems currently being addressed are the relatively high loss tangents of the practical ferroelectric materials and the large bias voltages required. This may be tackled by novel device structures and superconducting conductive materials. Prior to the discussion of ferroelectric tunable resonators, it is better to discuss and demonsterate some properties of ferroelectric materials.

3. Charcterisitics of the ferroelectric materials

An attractive and efficient material that has spontaneous polarization is a ferroelectric material. The presence of spontaneous polarization is highly temperature-dependent, and ferroelectric crystals generally have phase transitions where structural changes take place in the crystal [15]. The Curie temperature (Tc) is known as this transition temperature, at which the properties of the material change abruptly.

Thermodynamic properties show large anomalies, because the nature of the crystal structure close to the Curie temperature is totally changing. This is typically the case with the dielectric constant, which increases to a high value close to the Curie temperature, as indicated in **Figure 1**; it is also the transition point where the dielectric constant has the greatest sensitivity to the application of an electric field. This important characteristic can provide an attractive deployment of such materials for tunable electromagnetic components such as resonators, antennas, power dividers, hybrid couplers, and so on.

Several materials have shown a variable permittivity with the electric field, such as Strontium titanate (SrTiO3), Barium titanate (Ba, Sr. TiO3), (Pb, Sr)TiO3, (Pb, Ca)TiO3, Ba(Ti, Sn)O3, Ba(Ti, Zr)O3 and KTaO3 dopants [16–18].

However, strontium titanate (SrTiO3, STO) and barium strontium titanate (Bax Sr.(1-x) TiO3, BSTO), where x can vary from 0 to 1, are two of the most popular ferroelectric materials currently being studied for frequency-agile components and circuits. SrTiO3 is of special interest because of its crystalline compatibility with high-temperature superconductors (HTS) and its dominant properties at low temperatures.

Pure *STO* is not supposed to have Curie temperature above 0 Kelvin. Thin films and amorphous ceramic strucutres provide a low-temperature to achieve maimum dielectric constant. This implies that the Curie temperature is above 0 Kelvin,

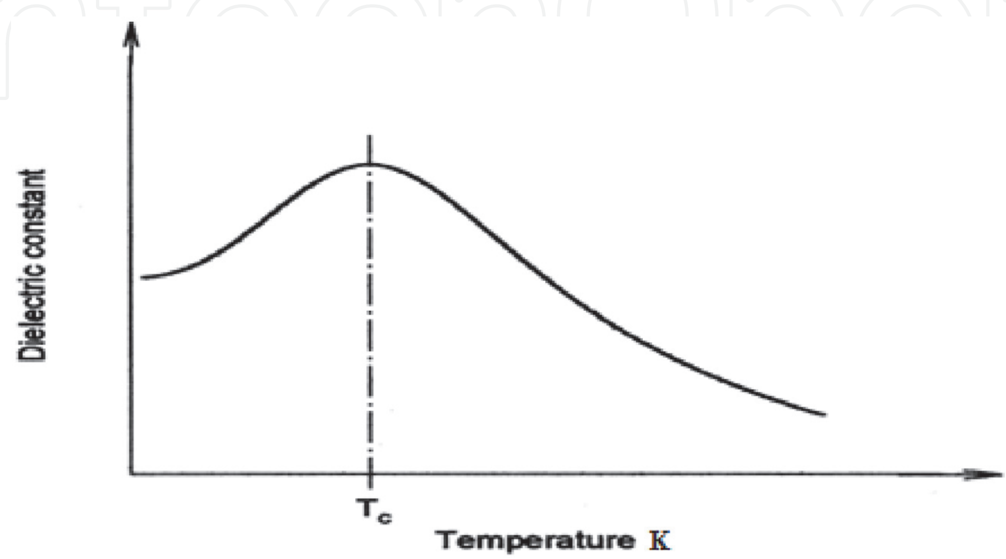


Figure 1.
Curve of dielectric constant as a function of temperature [3].

probably due to stresses or impurities in the films. For *BSTO*, as the value of x varies from 0 to 1, the Curie temperature varies from the value of *STO* to about 400 K, the Curie temperature of $BaTiO_3(BTO)$. This allows tailoring of the Curie temperature; generally, a value of $x = 0.5$ is used to optimize for room temperature, and a value of around 0.1 is used when the material is to be used in conjunction with HTS films.

For microwave and wireless communication applications, there are several different forms of ferroelectric materials that are of extrme interest. Over many years, single crystal materials have been studied. Thin-film ferroelectric materials have recently been investigated; these films have been manufactured by laser ablation and are very small in thickness, typically less than 1 μm. The films are also mainly deposited on the LaAlO-3 substrate of lanthanum aluminate (it is an inorganic substrate and was chosen to design the proposed ZOR resonator circuit) and are usually combined with single layers such as HTS or a top-surface patterned normal conductor. Tri-layer (substrate-superstrate-HTS) films, forming an HTS/Ferroelectric/HTS structure, have also been produced, however. Films on a sapphire substrate were also produced with a CeO 2buffer layer of cerium oxide to compensate for the mismatch between lattice and thermal expansion [19]. More recently, the sol–gel technique [20] has been developed for producing Barium Strontium Titanate (BST). This method can generate material that is about 0.1 mm thick.

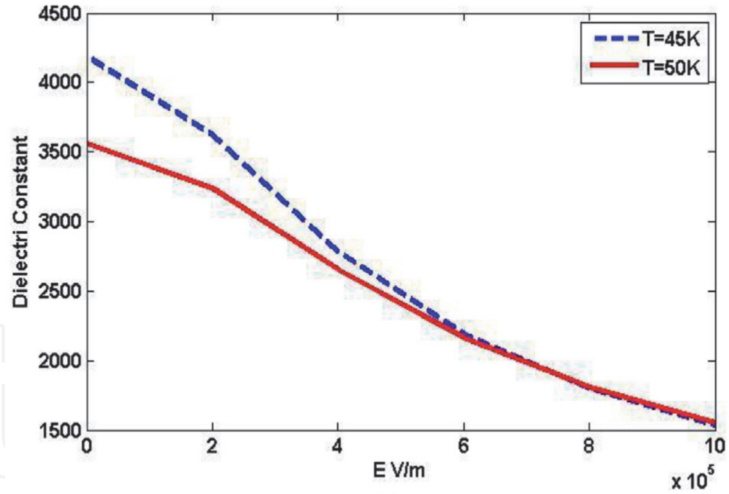
4. Thin film Sturucres dielectric properties

The dielectric constant of bulk single-crystal STO is known to be independent of frequency up to 100–200 GHz [21–24]. The electric field and temperature dependence of the dielectric constant of single-crystal STO measured using a disk resonator at microwave frequencies [25] is shown in **Figure 2** *(The Matlab source code for calculating dielectric constant against the temperature and electric field is included in Appendix).* As can be seen, at a low temperature, the variation in the dielectric constant against an applied dc electric field is more sensitive.

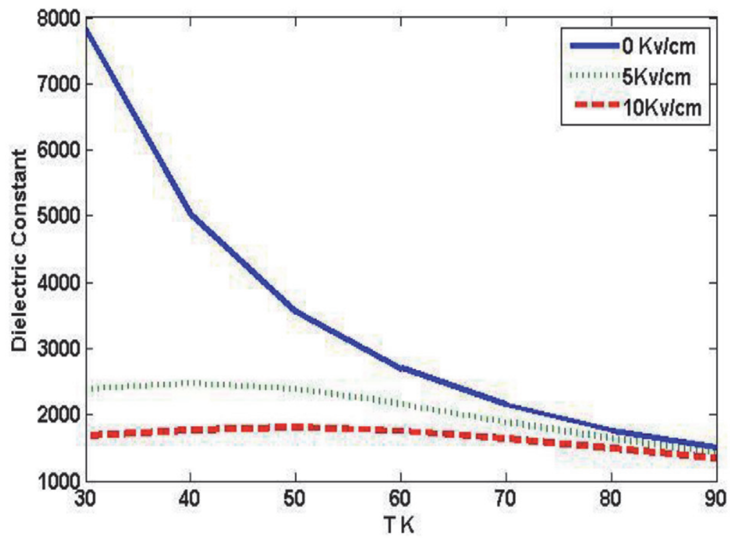
5. Properties of ferroelectric materials for microwave applications

The dielectric constant for thin films is normally lower than the single crystal with the same composition, and the loss tangent can be one order higher. An example of the temperature dependence of the bulk and thin-film BST permittivity is shown in **Figure 3** of [26]. It should be noted that the permittivity is substantially lower than the bulk for the BST thin film and the sharp peak is not observed at the phase transition temperature. The effect of size or the presence of dead layers, misfit strain and thin film defects are considered to be the sources of the deviation of properties from the behavior of the bulk [27]. The theory of this deviation, however, is not well understood yet.

The most fundamental characteristics for microwave applications are the dielectric constant, tunability, and loss performance of ferroelectric materials. It is clear that for high-performance devices, high tunability and low dielectric loss are favorable. In response to the applied electric field, which is the basis of microwave applications, the dielectric constant ε of ferroelectrics varies. Tunability is a criterion for evaluating the dependence on permittivity in the electric field. The tunability of a ferroelectric material, defined as the ratio of the dielectric permittivity of the material at zero electric fields to its permittivity under electric field bias E, can be defined in two ways.



(a)



(b)

Figure 2.
(a) Electric field dependence of the STO dielectric constant (b) temperature dependence of the STO dielectric constant at different dc electric fields [25].

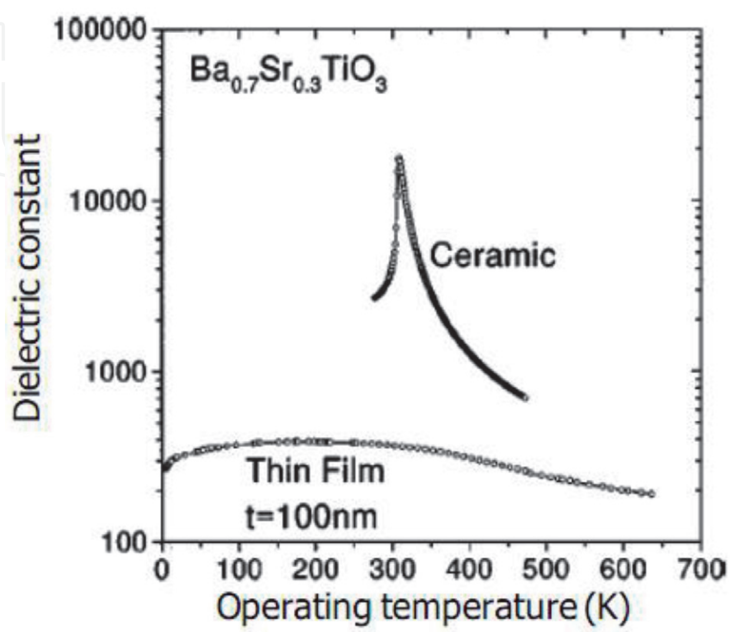


Figure 3.
Variation of the dielectric constant of a BST ceramic and thin film as a function of operating temperature [26].

$$\boldsymbol{n} = \frac{\boldsymbol{\varepsilon}(\mathbf{0})}{\boldsymbol{\varepsilon}(\boldsymbol{E})} \tag{1}$$

and the relative tunability $\boldsymbol{n_r}$ defined as the relative change of the permittivity between zero bias and an electric field $\boldsymbol{E}$ with respect to its permittivity at zero bias

$$\boldsymbol{n_r} = \frac{\boldsymbol{\varepsilon}(\mathbf{0}) - \boldsymbol{\varepsilon}(\boldsymbol{E})}{\boldsymbol{\varepsilon}(\mathbf{0})} = \mathbf{1} - \frac{\mathbf{1}}{\boldsymbol{n}} \tag{2}$$

6. Tunable composite right/left-handed transmission lines using ferroelectric thin films

Ferroelectric/superconductor thin films ($YBa_2Cu_3O_{7-\delta}/Ba_{0.0}Sr_{0.9}TiO_3$) are used to realize an electrically tunable, low-loss composite right/left-handed transmission line. A resistive line is deployed as both the DC bias path and RF choke. The whole device maintains a simple all-planar configuration. The composite right/left-handed transmission lines that are well-matched shows a wide passband [28].

Various tuning elements, such as surface-mounted discrete varactors or ferroelectric parallel plate varactors, have been used [29]. Through the series capacitors, tuning is accomplished, although tuning the capacitance and shunt inductance [30] simultaneously would be advantageous in maintaining the impedance match for critical requirements. Cables, the introduction of RF capacitive bases, decoupled capacitors [31], or more complicated networks trace the DC bias of the reported structures.

In this study, the tunable low-loss device is realized by planar ferroelectric/superconductor thin films. Tunable elements based on ferroelectric materials avoid surface mounting components compared to discrete diode varactors, so neither contact losses nor parasitics are present in the configuration. Furthermore, it is possible to continuously vary capacitance values.

The electrical tuning is based on ferroelectric permittivity's electric-field dependency. As the fundamental tuning element for its ability, between planar structures, to establish a relatively high electric field between its two electrodes, an interdigital capacitor (IDC) is used. Between the circuit layer (HTS) and the substrate, the ferroelectric thin film is sandwiched. Using a bias tee, the DC bias can either be excited through the RF ports or through an independent bias network with an RF choke. In that it introduces less interference to the main circuit and is often easy to fit into measurement systems, the previous approach is beneficial. However, due to the high-pass nature of a CRLH-TL, it is not straightforward to apply DC voltage through the RF ports.

In this case, we propose a resistive line approach as shown in **Figure 4** for a three unit cascaded CRLH-TL. The resistive line prevent the RF trnamission from flowing into the DC path if its resistance is sufficiently high. With line dimensions of 10μm wide, the simulated responses for different surface resistances are given in **Figure 5**. The attenuation losses are estimated 0.6 dB for 20Ω surface resistance, 0.3 dB for 0Ω, and 0.2 dB for 90Ω, corresponding to a line resistance of over 2, and 9 $K\Omega$ per unit-cell.

The substrate is 0.5 mm thick MgO. The ferroelectric material ($Ba_{0.0}Sr_{0.9}TiO_3$) is deposited on the upper side of the substrate. On top of BST, the $YBa_2Cu_3O_{7-\delta}$ ($YBCO$) is deposited and represents the superconducting circuit layer. Silver is used for the contact pads to reinforce the electrical connection with the on-wafer probes and bonding wires. The resistive line is made of titanium material that has surface resistance . The BST film has a measured permittivity of 400–500 with a loss tangent of 0.02–0.03.

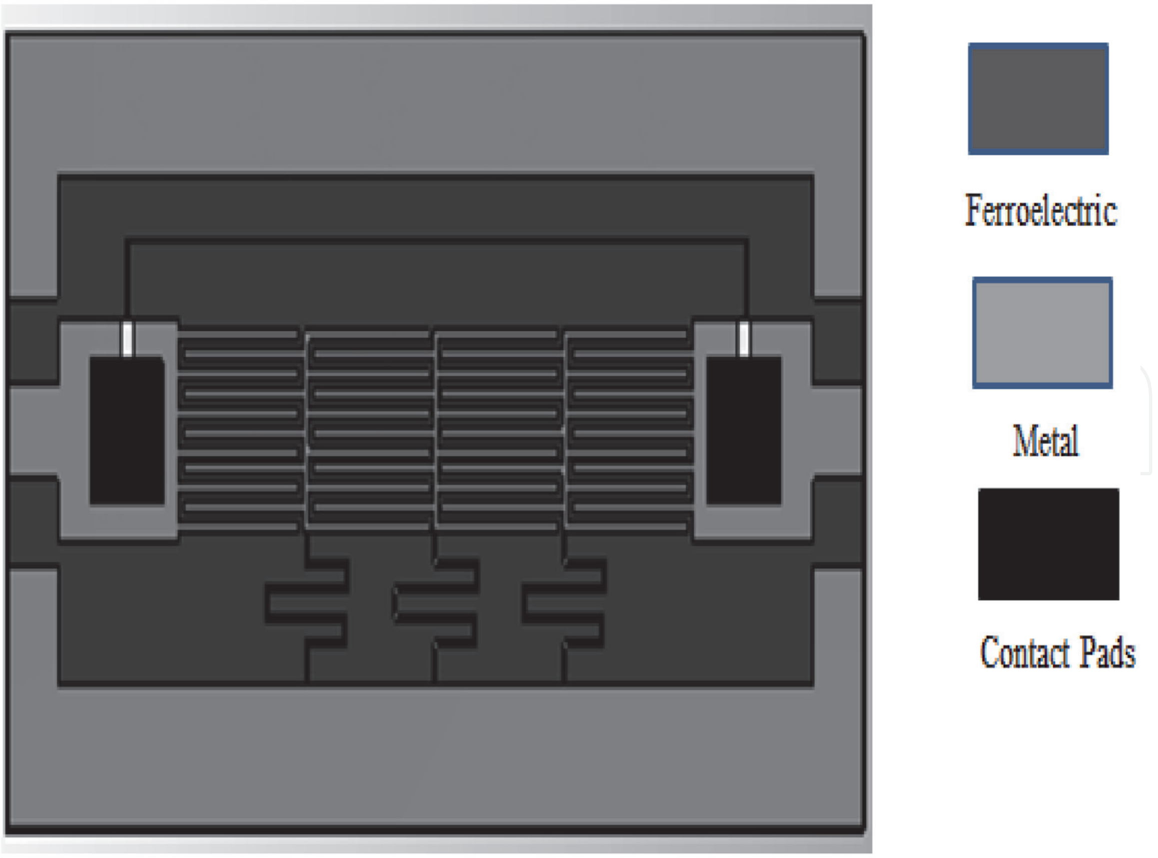


Figure 4.
Layout of a 3-unit CRLH-TL with resistive bias line, IDC, and meander line inductor [28].

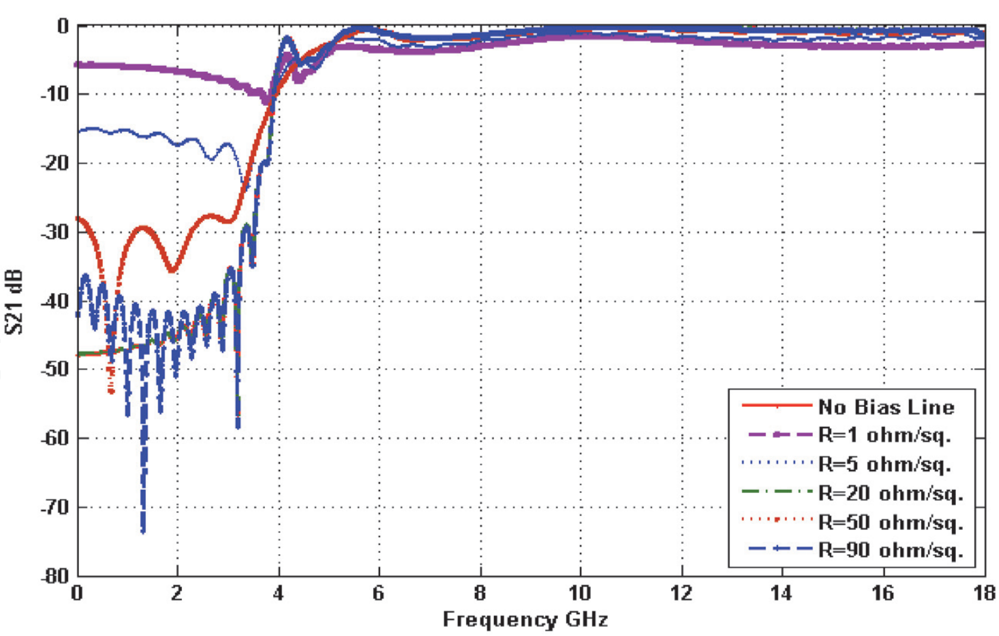


Figure 5.
Simulated responses of a 3-unit CRLH-TL with different surface resistances of the bias line.

The CRLH-TL single-unit shown in **Figure 6** was simulated and manufactured by [28]. It shows only the simulations, and the measurements are given in **Figure 7**. Within the bias range of 0-70 V, the return loss is better than −1 dB from 4 to 14GH.

Calculations show that 0.1 dB would have contributed to the ferroelectric loss (tan δ = 0.03). If the bias increases from 0 to 70 V (indicated by the effect of surface resistance variation), the phase shifts by 3.60 at 10 GHz in **Figure 8**.

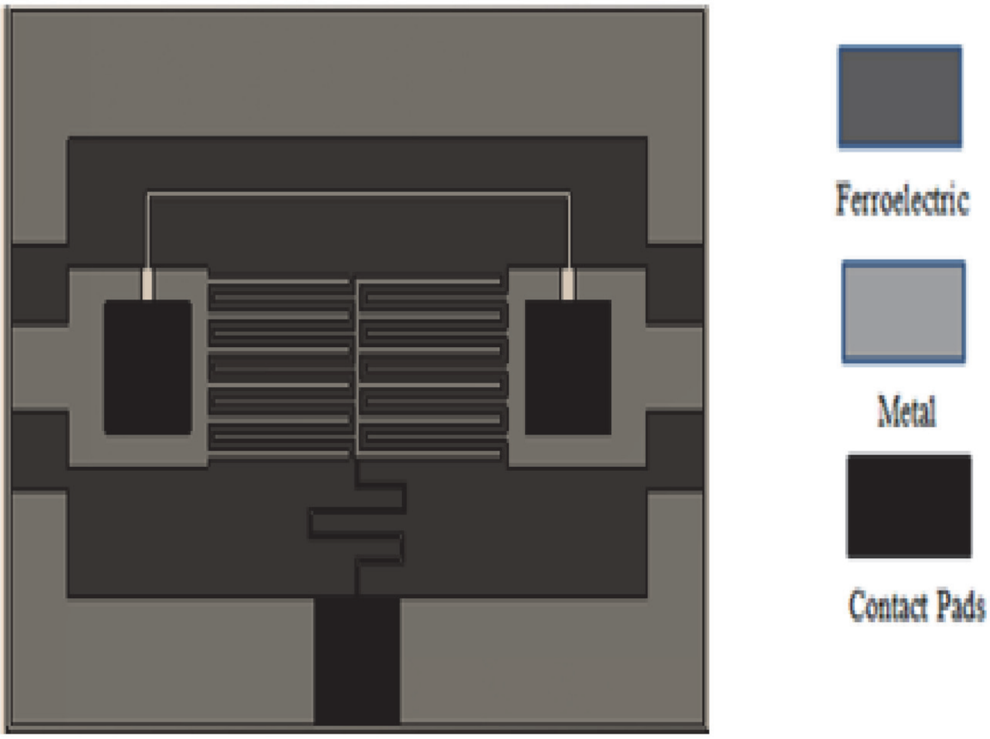


Figure 6.
Picture of the one-unit CRLH-TL [28].

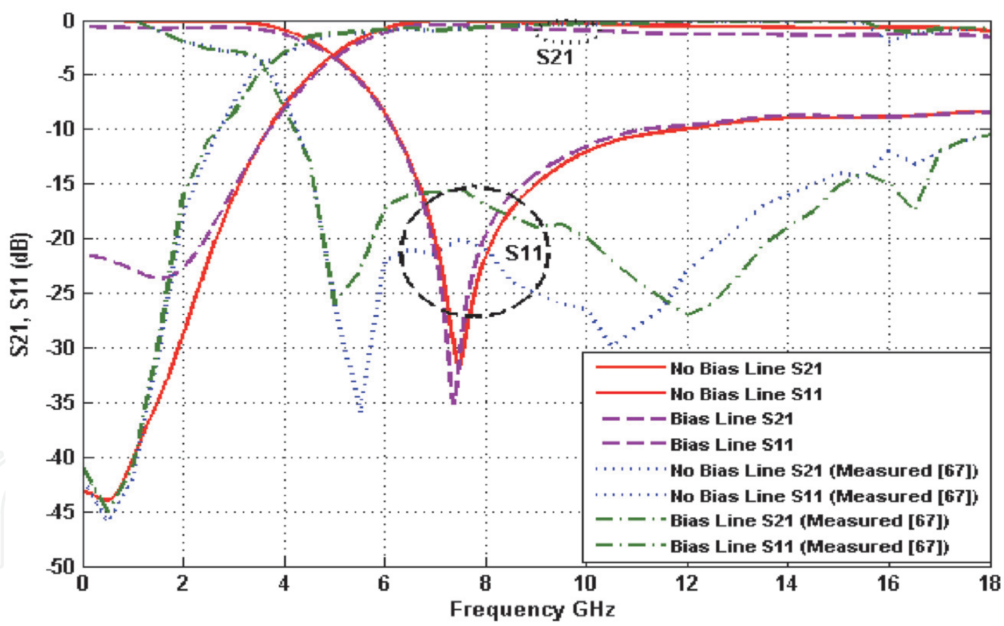


Figure 7.
Simulated responses of a one unit CRLH-TL with different surface resistances of the bias line [28].

7. Proposed tunable ZOR based on combined ferroelectric and HTS

Ferroelectric thin films can easily be incorporated into the CRLH MTM microstrip structure shown in **Figure 9**. For frequency-agile microwave communications systems, ferroelectric tunable microstrip structures are potentially attractive. These tunable components allow an innovative class of components with large frequency-agile tunabilities. Additionally, attenuation losses can be minimized when combined with HTS conductor for low-temperature applications. SrTiO3 (STO) thin films with large dielectric tunability and low loss tangents at microwave

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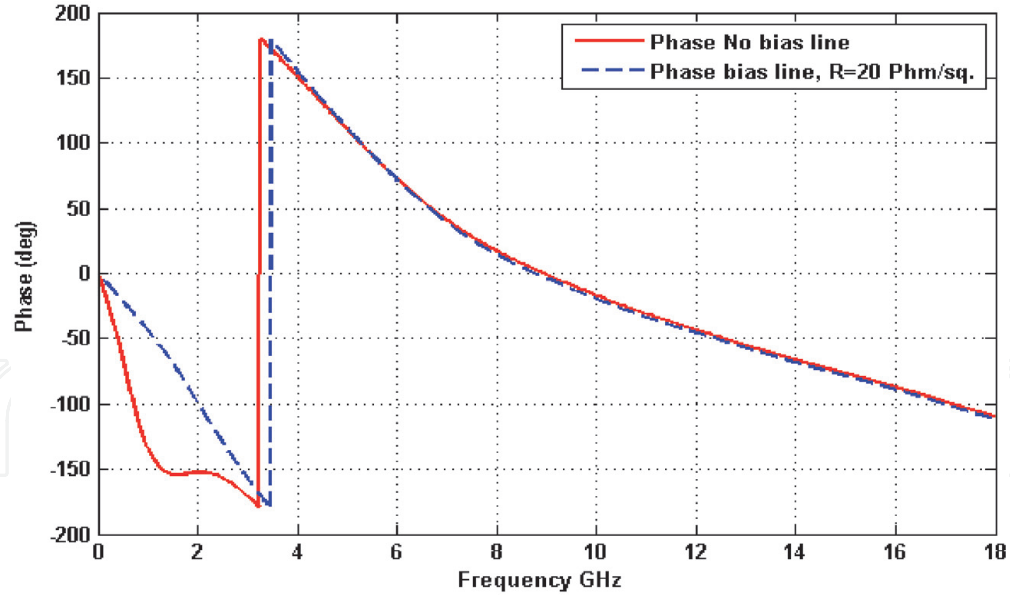


Figure 8.
Simulated phase responses and the phase shift of the one-unit CRLH-TL with two cases [28].

frequencies have been the most promising ferroelectrics for integration with HTS circuits [32]. The popular ferroelectric tunable structures are based on conductor/ferroelectric/dielectric two-layered microstrip.

The modified microstrip structure of **Figure 9** consists of a dielectric substrate (e.g., LAO or MgO, typically 254 to 500 um thick, LAO with permittivity 23.6 is selected to represent the base substrate [32], a ferroelectric thin-film layer

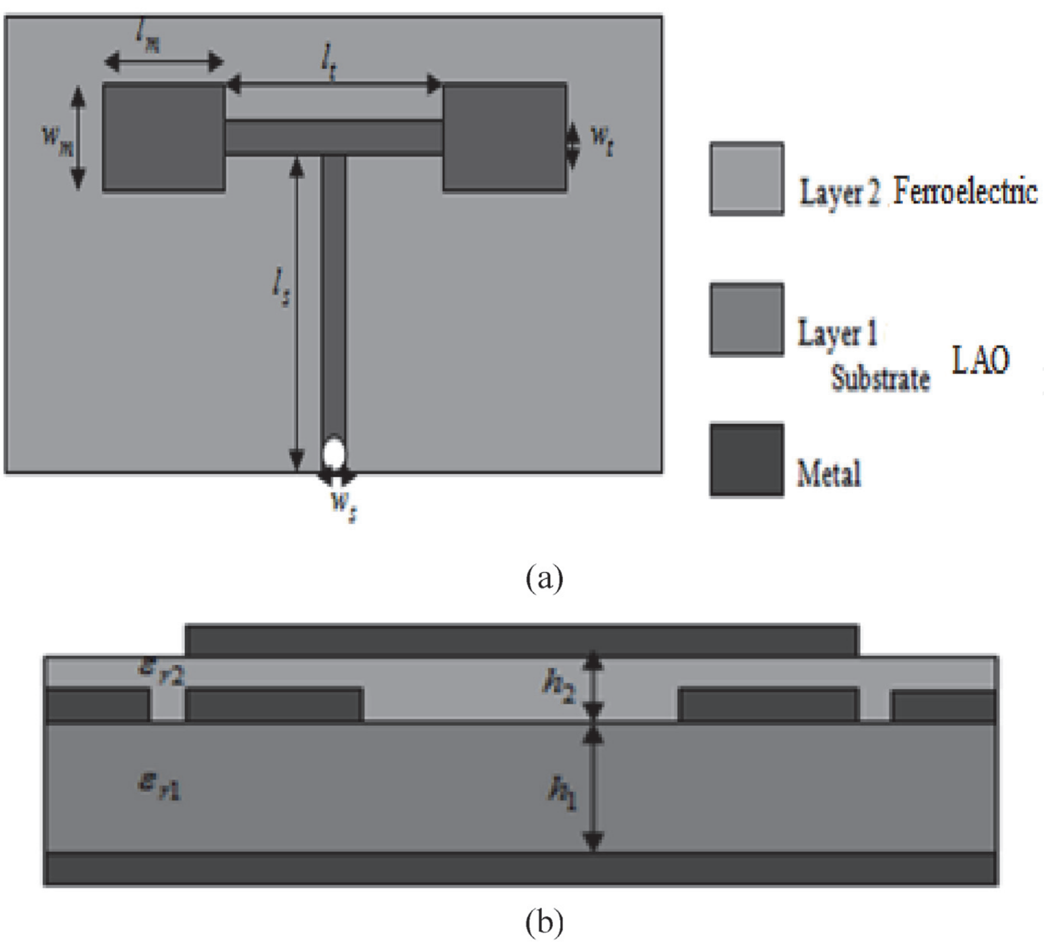


Figure 9.
Layout of ZOR with ferroelectric material (a) top view (b) side view.

(thickness."t_{ferro}" varying between 300 and 2000 nm for various applications), a gold or YBCO thin film ($2\mu m$thick or 300–600 nm thick, respectively) for the top conductor, and a $2\mu m$ thick gold ground plane. The STO film is a lossy dielectric that has a complex permittivity with a dielectric constant ε_r and a loss tangent $tan\ \delta$. Both of these parameters are functions of the DC applied electric field (E) and the temperature (T), and are introduced in the analysis by a phenomenological model developed by Vendik et al. [32] for a single crystal, and are given by [33]:

$$\varepsilon_r(T,E) = \frac{\varepsilon_{00}}{\Phi(T,E)} \tag{3}$$

$$tan\ \delta = tan\ \delta_1 + tan\ \delta_2 + tan\ \delta_3 \tag{4}$$

where

$$tan\ \delta_1 = A_1(T/T_0)^2/\Phi(T,E)^{\frac{3}{2}} \tag{5}$$

$$tan\ \delta_2 = A_2\Psi(T,E)^2/\Phi(T,E) \tag{6}$$

$$tan\ \delta_3 = \frac{A_3 n_d}{\Phi(T,E)} \tag{7}$$

and

$$\Phi(T,E) = \left[\left(\xi^2+\eta^3\right)^{\frac{1}{2}}+\xi\right]^{\frac{2}{3}} + \left[\left(\xi^2+\eta^3\right)^{\frac{1}{2}}-\xi\right]^{\frac{2}{3}} - \eta \tag{8}$$

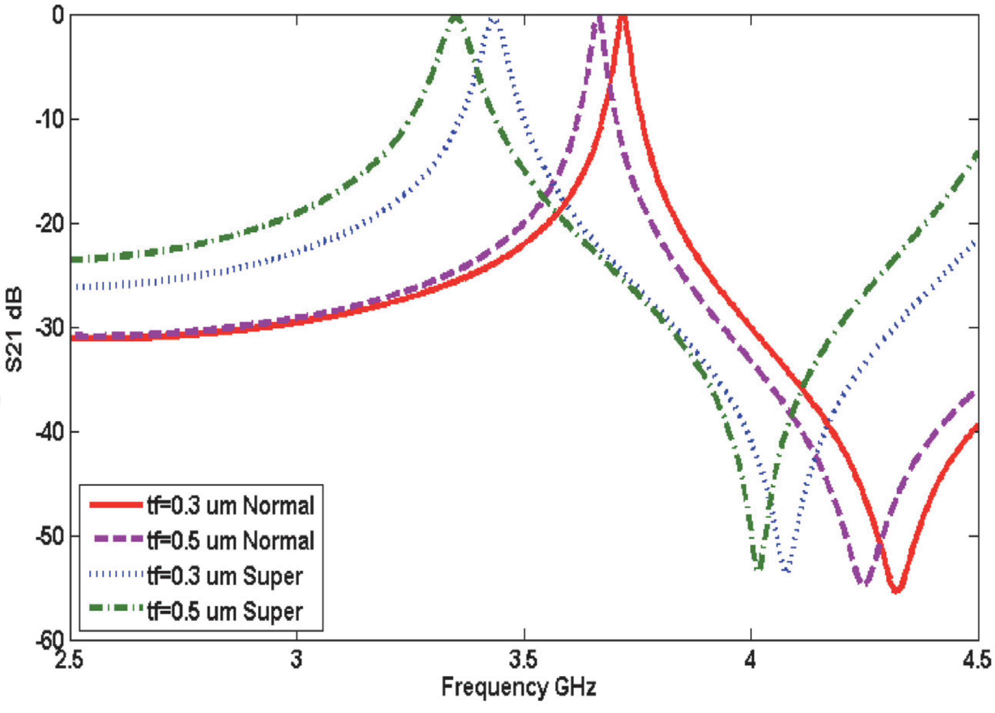
$$\Psi(T,E) = \left[\left(\xi^2+\eta^3\right)^{\frac{1}{2}}+\xi\right]^{\frac{1}{3}} - \left[\left(\xi^2+\eta^3\right)^{\frac{1}{2}}-\xi\right]^{\frac{1}{3}} \tag{9}$$

$$\xi(E) = \sqrt{\xi_s^2 + (E/E_N)^2} \tag{10}$$

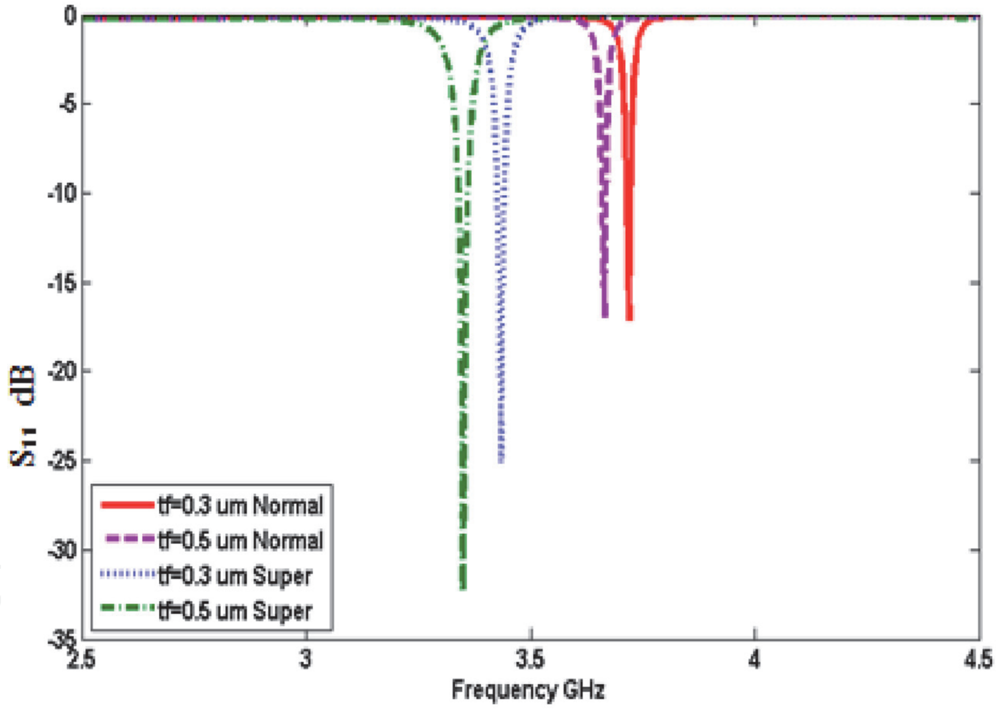
$$\eta(T) = \left(\frac{\Theta}{T_0}\right)\sqrt{(1/16) + (T/\Theta)^2} - 1 \tag{11}$$

In the previous equations, ε_{00} is a constant analogous to the Curie constant, E_N is the normalizing applied electric field, ξ_s is the rate of crystal strain, a measure of the density of defects, Θ is the effective Debye temperature, and T_0 is the effective Curie temperature. Numerical values for these model parameters for a single crystal of STO are given by [34]: ε_{00}= 2080, E_N = 19.3 KV/cm, ξ_s= 0.018, Θ= 17 K, and T_0= 42 K. The change of dielectric constant with frequency is generally small in the microwave frequency range. In Eqs. (5), (6) and (7) A_1, A_2, *and* A_3 are material parameters, and n_d is the density of charged defects. For high-quality crystals, tanδ_3 is small with respect to tan δ_1 and tan δ_2 and can be neglected. Numerical values for A_1 *and* A_2 parameters for STO at a frequency of 10 GHz are given by [35]: $A_1 = 2.4 * 10^{-4}$ and $A_2 = 4 * 10^{-3}$.

Figure 10 depicts the magnitude of the transmission scattering parameter (S21) for 0ΩYBCO/STO/LAO microstrip line CRLH ZOR shown in **Figure 9**, with a 0.3 μm STO thin film. It provides the STO permittivity dependence on its thickness. **Table 1** summarizes the plotting curves given in **Figure 10(a, b)**. As we see, for a given frequency, the attenuation increases with film thickness. At higher frequencies, because of the skin depth effect, more RF field is concentrated in the ferroelectric film and less is concentrated in the dielectric substrate, resulting in larger insertion loss. As the value of the ε_r increases, the attenuation also increases. This is a consequence of mismatches resulting from the decrease in Z_o.



(a)



(b)

Figure 10.
Variation of the magnitude of the transmission coefficient with the frequency at a different ferroelectric thickness t_{ferro}*. (a)* S_{21}*. (b)* S_{11}*.*

$t_{ferro}(\mu m)$	Normal 300 K		Super 77 K	
	$f_{res}(GHz)$	S_{21} dB	$f_{res}(GHz)$	S_{21} dB
0.3	3.71	−0.95	3.43	−0.29
0.5	3.66	−0.97	3.5	−0.34

Table 1.
Parameters values of ***Figure 10****.*

Temperature ($^o c$)	ε_r	$tan\delta$ *10^{-4}
−50/223 K	438	4.1
−25 /248 K	380	4.5
0/273 K	3 0	4.8
+25/298 K	320	5.2

Table 2.
Dielectric constant and loss tangent of single-crystal SrTiO3 material at various temperatures.

$T(K)$	ε_r	$f(GHz)$	S_{21} dB
30	7811	3.41	−0.25
60	269	3.5 3	−0.21
77	1867	3.56	−0.22

Table 3.
*Parameters values of **Figure 11**.*

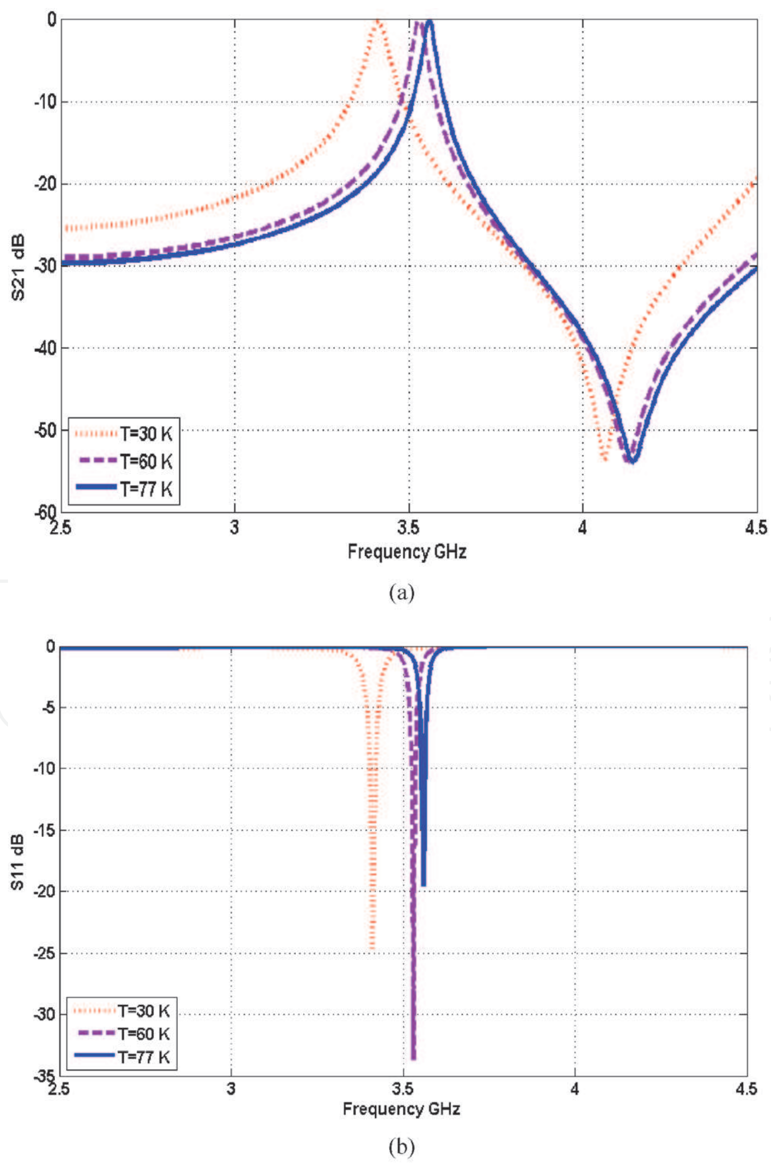


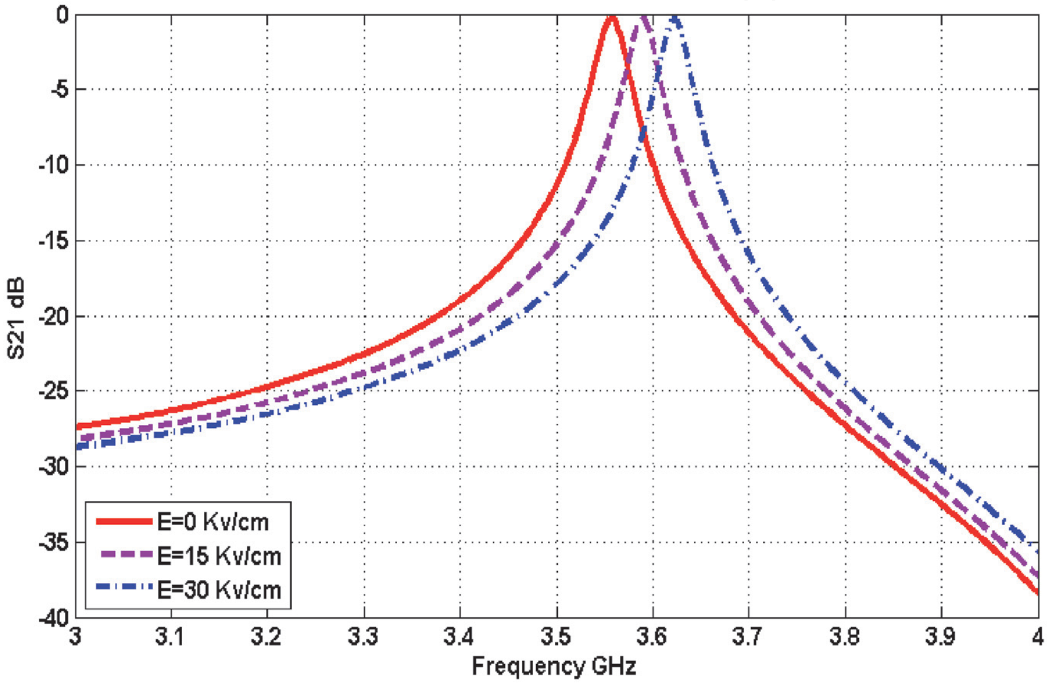
Figure 11.
Variation of the magnitude of the transmission coefficient with the frequency at different operating temperature T. (a) S_{21}. (b) S_{11}.

The temperature dependence of ε_r and $tan\ \delta$ for single-crystal SrTiO3 ferroelectric material has been reported by Krupka et al. [36] and is summarized in **Tables 2** and **3**.

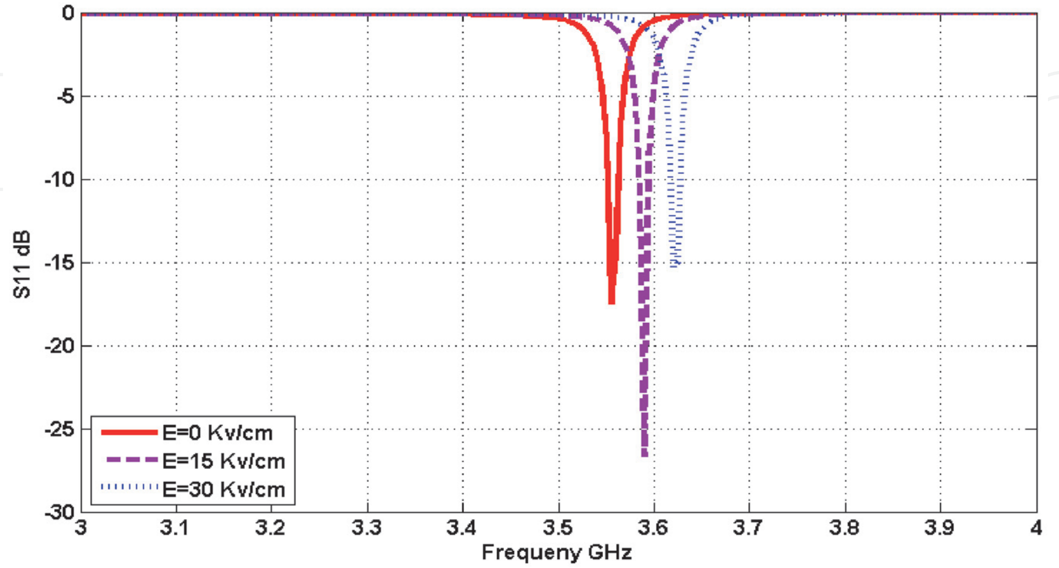
Figure 11 shows the variation of resonance frequency with the temperature which is very attractive at very low temperatures.

The data were conducted at 77 K in the 2.5 to 4.5 GHz frequency range. It is worth to observe that, at no bias and at 3 GHz, the insertion loss IL = 0.2 dB. These simulated data are not de-embedded, meaning that any contribution from the SMA launchers used for the measurement to the overall insertion loss has not been compensated from the data.

Figure 12 and **Table 4** indicates the effect of E-field on the response of ZOR, the E-fields is varying from 0 to 30 Kv/cm. If the sample kept at a constant temperature



(a)



(b)

Figure 12.
Variation of the magnitude of the transmission coefficient with the frequency at different electric field E. (a) S_{21} (b) S_{11}.

$E(Kv/cm)$	ε_r	$\tan\delta$ *10^{-4}	$f(GHz)$	S_{21} dB
0	1867	7.2	3.55	−0.25
1	1168	18.5	3. 59	−0.28
30	741	26	3.62	−0.39

Table 4.
Parameters values of ***Figure 12*** *at T = 77 K.*

Property		MIM	HTS 77 k [Proposed]	Ferro+ Copper [Proposed]	Ferro+ HTS 77 k [Proposed]
Performance	S_{11}	−10	−34	−18	−32
	S_{21}	−3.55	−0.09	−0.54	−0.023
Tunability		No	No	Yes	Yes
Q factor		1762	43411	9957	68714
Fabrication		Simple	Difficult	Simple	Difficult

Table 5.
A comparative study of the different ZOR structures.

of 77 K, the ε_r STO is reduced from a high value of approximately 1867 at zero bias to a lower value of 741 at a high bias field.

The dynamic range of dielectric tunability with low additional microwave dielectric losses due to the insertion of ferroelectric thin films is one of the important criteria for the use of ferroelectric thin films in tunable circuits. Dielectric tunability is defined as the ($\varepsilon_r(0)$ at zero bias – $\varepsilon_r(E)$ at large bias)/ ε_r at zero bias.

$$n = \frac{\varepsilon_r(0) - \varepsilon_r(E)}{\varepsilon_r(0)} \tag{12}$$

Dielectric tunability as high as 90% is attainable in STO thin films at moderate loss-tangent values (typical values between 0.005–0.01 at GHz frequencies) [37]. So, this structure will provide a tunability up to 47% for E = 30 kV/cm.

Table 5, demonstrates the comparison between the four proposed structures stated as:

Case 1: The MIM with a normal conductor (Copper).

Case 2: Adding HTS in replace of Copper to the MIM.

Case 3: Adding the ferroelectric material in case of Copper.

Case 4: Adding the ferroelectric material in case of HTS.

8. Conclusions

A tunable ZOR CRLH resonator is successfully illustrated using a thin film ferroelectric material. ZOR can be applied to the ferroelectric material and this provides a different resonance frequency by altering either the electric field applied or the operating temperature. In addition, the incorporation of HTS material in place of normal conductors (e.g., gold, copper) significantly reduced conductor losses and consequently improved circuit performance. Therefore, for the development of low-loss and tunable microwave components and systems for wireless, radar and satellite communications, the design, manufacture and optimization of

HTS/ferroelectric hybrid circuits may be of great interest. Tunable HTS/STO/LAO ZOR resonators have a more than 47 percent frequency tunability factor and have been demonstrated at 77 K.

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Conflict of interest

No conflict of interest.

Appendices

Ferroelectric Characterization:

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clear all
close all
clc
ck=8.7e+4; % Curie constant
e0=8.85e-12;
dn=2;
es=0.018;theta=175;a1=2.45e-4;t0=42;a2=4e-3; % Constants
e00=ck/t0;
En=(2*dn)/((e0)*(3*e00)^(3/2));
t=[77] %operating temperature
for j=1:1:length(t)
eta=((theta/t0)*sqrt((1/16)+(((t(j))/(theta))^2))-1) %eta(T)
  E=0:1e5:30e5 %operating electric field
for i=1:1:length(E)
    e(i)=sqrt((es^2)+((E(i)/En)^2)); %e(E)
    x(i)=(((e(i)^2)+(eta^3))^0.5)+(e(i));
    y(i)=(((e(i)^2)+(eta^3))^0.5)-(e(i));
    phi(i)=((x(i))^(2/3))+((y(i))^(2/3))-(eta);%phi(T,E)
    er(i,j)=(e00)/(phi(i)) %permittivity
    epsi(i)=((x(i))^(1/3))-((y(i))^(1/3)); %epsi(T,E)
    delta2(i)=((a2)*(epsi(i))^2)/(phi(i)); % tan delta2
    delta1(i,j)=((((a1)*(t(j)/t0)^2))/(phi(i))^(3/2)); %tan delta1
    delta(i,j)=delta1(i,j)+delta2(i)          % Total Tangetial loss
    n=er/er(i)

end
```

```
      plot(E,er)

   end
    figure
      plot(E,delta)
```


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