TUNABLE SUPERCONDUCTING BAND-STOP FILTERS

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ABSTRACT

Electrically tunable notch filters based on bulk single crystal $SrTiO_3$ (STO) parallel-plate resonators with High Temperature Superconducting (HTS) electrodes are reported. The filters operate at temperatures below 90 K. The center frequency, located in the range 0.5-2.0 GHz, can be controlled with an applied voltage, in some cases more than 100%. Filters are designed for operation at high microwave power levels in advanced wireless communication systems.

INTRODUCTION

A critical issue in the development of multi-channel microwave communication systems operating in the 1-3 GHz frequency band is the reduction of size of the microwave components, and particularly filters. The potential of miniaturization of microwave devices based on integration of high dielectric constant ferroelectrics, e.g. Strontium Titanate (STO), and superconductors, e.g. $YBa_3Cu_3O_{7-x}$ (YBCO), is discussed in [1]. The dielectric constant of STO is more than 2000 below 90 K and depends strongly on applied DC electric field [1], [3] and temperature [2]. In the frequency band 1-3 GHz the wavelength in a microwave transmission lines based on STO is in the range only 0.2-0.6 cm. It is also well established that HTS thin films (e.g. YBCO) grown on STO substrates have very low surface resistance. Thus, the integration of HTS (e.g. YBCO) and non-linear dielectrics (e.g. STO) results in a drastic reduction of size and losses of microwave components, such as resonators, filters, and enables development of electrically tunable devices.

In this paper we present electrically tunable band reject filters operating at cryogenic temperatures. Instead of thin ferroelectric films we use bulk single crystal STO since it has higher dielectric constant and lower losses in comparison with the thin films produced today. Additionally the volume of the resonators and hence the microwave power handling capability can be substantially higher in comparison with thin film filters.

PARALLEL-PLATE RESONATORS

Parallel-plate resonators are formed by deposition of thin HTS films on both surfaces of circular or rectangular STO crystals. The superconducting plates of the resonator are made slightly smaller than the crystal geometries to account for mechanical tolerances and achieve a close control over the resonant frequency. The thickness of the superconducting plates are typically 0.3-0.4 µm. They are partly or completely covered with normal conductor films (e.g. Au) to make ohmic contacts for the DC bias. The typical sizes are 2.0 x 2.0 x 0.5 mm^3 for rectangular resonators, and 5 mm or 10 mm in diameter for circular disks.

The resonators are electrodynamically thin, i.e. the thickness is smaller than the wavelength of the microwave signal at lower order modes, so that only TM modes are exited [3]. The thickness is chosen from practical considerations. Thicker resonators suggest that the resonator can support higher microwave powers, which on the other hand may lead to unpractical high control voltages. In our experiments all resonators are 0.5 mm thick and the maximum voltages required are about 500 V.

Although the resonators may be designed to have any shape, circular seem to be the most practical, as shown in Fig. 1.

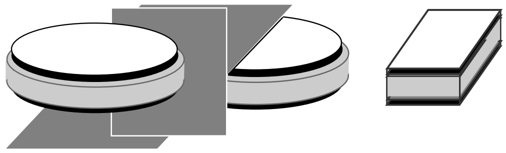

Figure 1: Parallel-plate resonators

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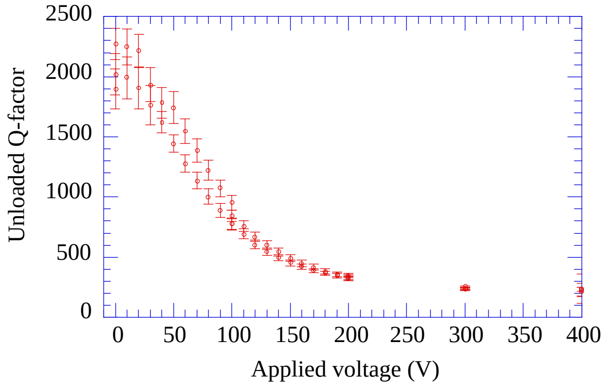

Figure 2: Performance of a circular STO disk resonator.

Before possible filter applications we performed an extensive experimental study of the dielectric properties of STO and microwave performance of the resonators using single port resonant measurements. In these measurements the resonators are enclosed in a specially designed coaxial package with a heat sink for cryogenic operation. The DC bias is applied through a high voltage bias tee, and the measurements are performed either in liquid Nitrogen or in a two stage cryo-cooler using a computer controlled Wiltron 360B network analyzer. A typical bias dependence of the unloaded Q-factor of a circular disk resonator at 50 K is shown in Fig. 2. Although the Q factor at zero bias is rather high it decrease drastically with applied electric field. At higher temperatures (77K and above) the peak of the curve is slightly flat and tuning of the resonance frequency in a small frequency range may be performed where the Q-factor is still reasonably high. It should be noted that if the resonators are cooled with short circuited plates a double hysteresis loop, fig. 2a, may appear in the voltage dependence of the resonant frequency [4]. Otherwise neither the dielectric hysteresis, nor the hysteresis in the microwave losses are substantial.

The results of the reflection measurement described above are used in an MDS optimization procedure to extract lumped element parameters of the equivalent parallel circuit model of the resonator. The extracted parameters are: C=1360 pF, L=0.026 nH, R=430 Ohm, Q=3000 at zero volt , 0.83 GHz and 77 K.

This and similar resonators are used in single and double (two resonator) pole band-reject filters. Some of the resonators have been cut to make half disks and square resonators used in our experiments.

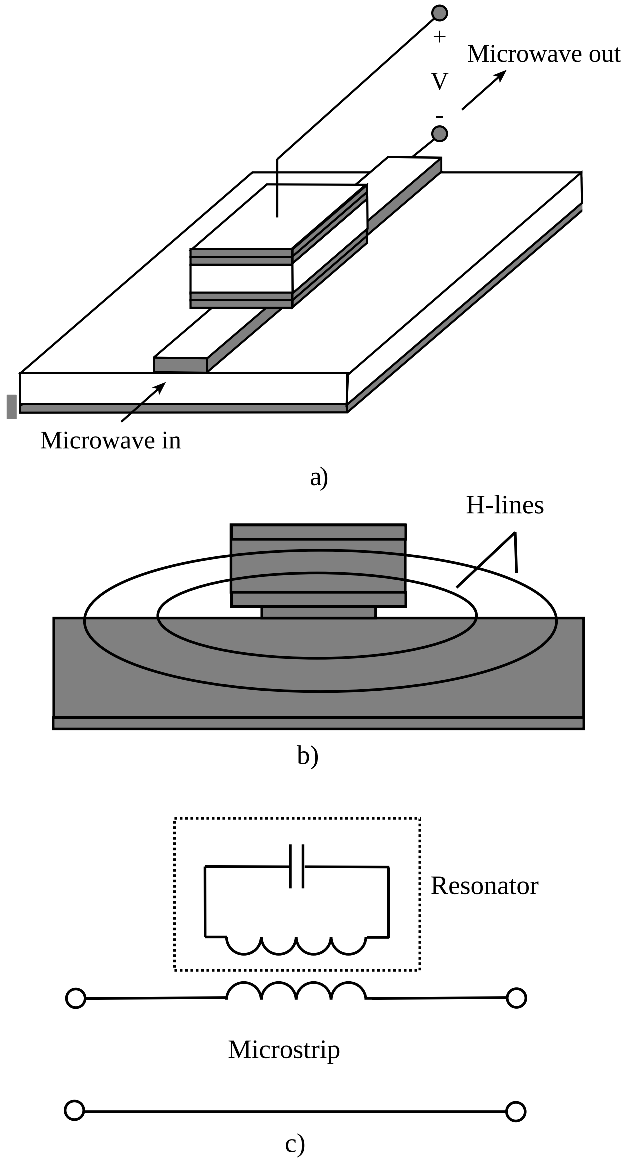

Figure 3: Design of microstrip loaded notch microstrip filter a) and cross section of the filter with magnetic field lines (a), and its equivalent circuit (b)

PERFORMANCE OF BAND-STOP FILTERS

i) Microstrip loaded band-stop filters

The simplest filters are arranged by attaching square shaped parallel-plate resonators on top of microstrip lines. In our experiments we used a 50 Ohm copper microstrips line on an 0.5 mm thick alumina substrate. To ensure low out of the rejection band losses use of HTS microstrips could be more desirable. Fig. 3 show one resonator single pole filter design where the lower plate of a square

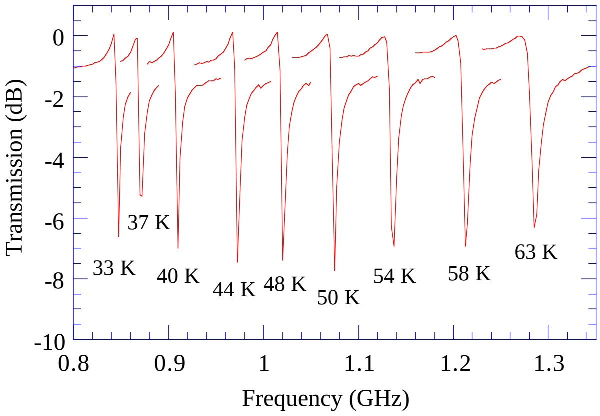

Figure 4: Temperature dependence of the first rejection band of the notch filter (not yet optimized).

resonator form ohmic contact with a microstrip transmission line. The filters are enclosed into a package with input/output SMA connectors. The package is designed for cryo-cooling. The DC bias is applied through the microstrip using bias tees external to the package. A small diameter inductive wire via a dielectric isolator in the lead of the package used to bring the bias voltage to the upper plate of the resonator. The orientation of the parallel-plate resonator is chosen so that the magnetic field lines of the microstrip and resonator coincide ensuring maximum inductive coupling between resonator and microstrip, Fig. 3b. The coupling strength is controlled by proper design of the width of the contacting sections of the microstrip and lower plate of the resonator. Thus, a series resonant circuit is inserted into the microstrip, Fig. 3c, which acts as a band reject filter. The DC bias applied to the plates changes the dielectric constant of the STO and the resonant frequency of the parallel-plate resonator. Dual mode operation can be achieved by etching away a portion of one of the corners of the upper superconducting plate. In the experiment the dual mode operation of the

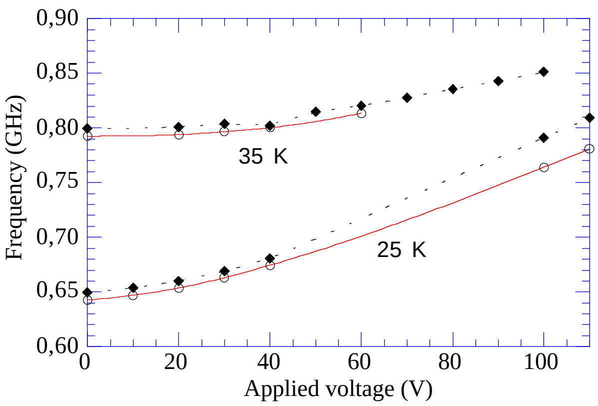

Figure 5: Dependence of the degenerate mode frequencies on DC bias.

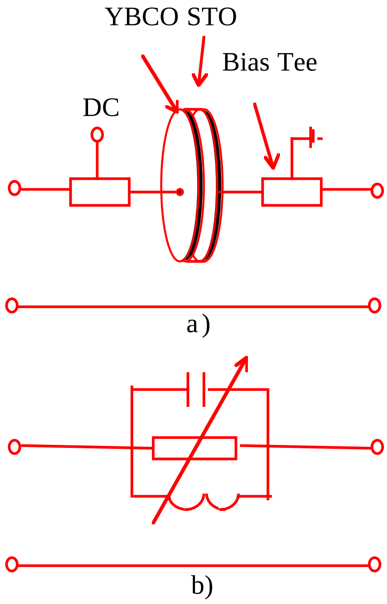

Figure 6: Schematics (a) and the simple equivalent circuit (b) of a tunable circular disk resonator filter

resonator is achieved by changing the orientation of the parallel-plate resonator to form an angle of 45^{o} with the microstrip. The positions of the stop-band of a single pole filter at different temperatures at zero bias are shown in Fig. 4. The dependencies of the resonant frequencies of the two degenerate modes upon applied DC bias are shown in Fig. 5. Tunabilities, $(f-f_0)/f_0$, as large as 50% are archived at higher applied voltages (500 V), and lower temperatures.

ii) Circular resonator based band-stop filters

Single pole and dual pole tunable rejection filters are also realized using circular resonators. These resonators have higher Q-factors and can handle higher microwave powers in comparison with rectangular ones. In a single pole filter, shown schematically in Fig. 6, the axially symmetric TM_{020} mode, which has the highest field confinement, controllability and Q-factor [3], is utilized. Both single and double resonator filters are enclosed into specially designed packages to reduce the radiation losses and allow cryogenic cooling. Package walls are about 5 mm away from the parallel-plate resonator to minimize losses in the package walls. A typical S parameter measurement result for a single pole resonator is shown in Fig. 7. A typical dependence of the rejection band central frequency on the applied DC voltage at 60 K is shown in Fig. 8.

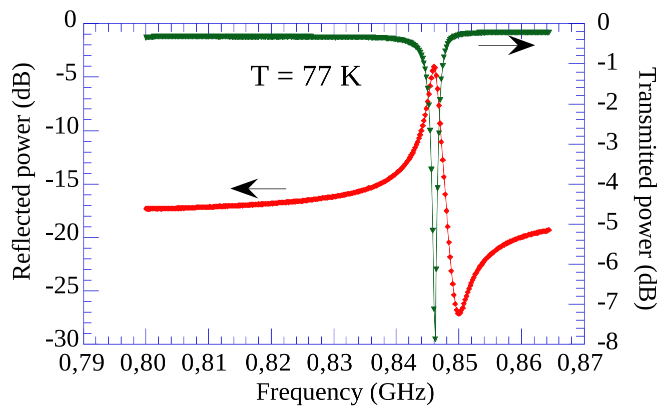

Figure 7: Measured reflection and transmission of a single pole rejection filter at zero bias voltage

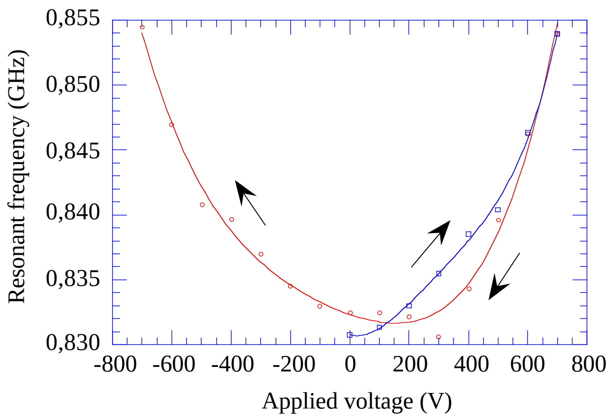

Figure 8: Measured dependence of the center frequency on bias voltage at 77 K. Arrows indicate the sequence of applied voltage. Hysteresis is due to the HTS/STO interface.

CONCLUSIONS

Due to the small sizes and large tuning range the integrated HTS/ferroelectric rejection filters can particularly be used in Cellular Communication Systems operating in the frequency band 1-2 GHz. In comparison with the thin film stripline (microstrip etc.) superconducting filters the above filters handle much higher microwave powers.

Despite the attractive features there are still some material related problems which has to be addressed. First of all it is the sharp dependence of the microwave losses with applied DC field. It is believed that this problem may be solved by improving the single crystal STO quality, and by reducing the effects from superconductor/STO interfaces by careful preparation of the conducting plates. Another important issue which can cause problems is the initial conditions (temperature, mechanical stresses, cooling conditions etc.) before operation of the STO based resonators and filters, since in some cases STO crystal may exhibit a high voltage hysteresis in the bias dependent dielectric constant [4].

ACKNOWLEDGMENT

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