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Design of Narrow-Band Tunable Band-Pass Filters Based on Dual Mode $SrTiO_3$ Disc Resonators

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Abstract — **Design of four-pole band-pass tunable filters based on two dual mode STO disc resonators (0.5mm thick, 7.0 mm in diameter) is reported. Chebishev filters without and with transmission zeroes are realized utilizing two degenerate TM_{110} modes. Experimentally obtained Q-factor and resonant frequency of the disc resonators are used in filter simulations. The filters are designed for operation at 60 K with center frequency 0.5 GHz and bandwidth less than 2.0 %. The tunability (fractional change in center frequency) of the filters is about 8%.**

I. Introduction

Parallel-plate circular patch [1] and disc [2] resonators seem to be attractive for high power and tunable filter applications. To make the resonator electrically tunable its dielectric filling usually is made of a nonlinear material, such as single crystals paraelectric $SrTiO_3$ (STO) [3] and $KTaO_3$, (KTO) [4]. To get a DC field dependent dielectric permittivity (tunability) these materials need to be cooled below 100 K, where the permittivity is larger than 1000. Applying a DC bias to the plates of the resonator causes a reduction of the permittivity and leads to increased resonance frequency. To keep the DC bias voltages low the resonator is usually made thin. Such resonator is usually also electrically thin, i.e. its thickness d is much smaller then the wavelength of the microwave signal, and lowest order modes are essentially of *TM* type [2]. Due to the excellent dielectric properties, no leakage currents are generated and hence no DC power is consumed for tuning. However, the Q-factor of resonators made of *STO* and *KTO* decrease drastically, typically from several thousands at zero bias to several hundred at DC field above 10 kV/cm. Fig.1 show typical experimental performance of a single crystal STO disc resonator with evaporated Cu plates. For comparison the expected Q-factor for High Temperature Superconductor (HTS) plates are also shown [5]. The drastic reduction of the Q-factor at high DC field sets the application limits in terms of maximum tunability and minimum insertion losses. Low loss narrow band tunable filters may be realized with HTS plates at low DC bias fields, where the Q-factor is still rather high (i.e. >1000). It is clear that the tunability of such a filter is small. Filters with a larger tunability may be utilized if higher losses (at high DC bias fields) are acceptable. In this case, Cu or Au plates instead of HTS may be used.

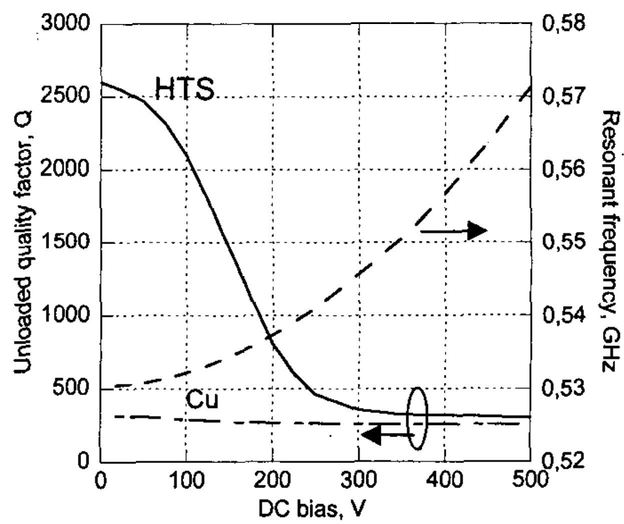


Fig.1 Experimental dependence of the resonant frequency and unloaded Q-factor of an STO parallel-plate circular resonator at 60 K. The disc is 0.5 mm thick and 7.0 mm in diameter with 4.0 μm thick Cu plates.

In a previous work [6] an experimental two-pole tunable filter was realized using two KTO disc resonators, where a transmission pole was introduced at the high frequency skirt making the filter useful for high power duplexer applications. The filter was designed for operation at 77 K with pass-band 1.5% and center frequency 0.9 GHz. The in-band insertion losses of this filter changed in the range 1.6÷4.7dB where the DC tuning voltage was changed from 0 to 500 V. On the other hand it is known that the minimum of the losses in STO crystals is about 60 K [3]. Having this in mind in this work, the designs of two narrow band filters for operation at 60 K are given. In these four-pole filters only two STO disc resonators are used in dual mode regime to bring the costs and the sizes down. Additionally, to improve the selectivity, in one of the filters transmission poles are introduced at the low and high frequency skirts. Filters are designed on single crystal STO disks with copper electrodes. A perturbation is introduced in one of the plates to facilitate coupling between two degenerate TM_{110}.

II. Design Of Filters

The design of filters consists of several steps. In the first step we made experimental characterization of the disc resonator with copper electrodes at 60K in DC bias range 0-500V. The results of the measurements are shown in Fig.1. The measured Q-factor is in the range 310-250 under 0-500V of applied voltages. The measured average susceptance slope parameter in the frequency range 0.53-0.57 GHz is $b = 2.25$ S. The relative change in the resonant frequency (i.e. tunability) is about 8%. The data obtained from the measurements are used in filter simulations.

In the second step, we analyze the dual mode operation of the STO resonator utilizing two degenerate TM_{110} modes with orthogonal polarization. Fig.2a depicts the vector plot of the magnetic field of TM_{110} mode between the plates of the resonator. The coupling between the orthogonal modes is controlled by size of perturbation (slit), Fig.2b, in such a way that desired strength is be obtained. The dielectric permittivity of STO at 60K extracted from measured resonant frequency and size of the disc resonator is 2650. It is used in HFSS simulations for the analysis of the coupling strength between modes as function of slit size. The results of simulations are summarized on Fig.2c, where coupling bandwidth $\Delta f = f_e - f_o$ (f_o, f_e - are odd and even mode resonant frequencies respectively) is plotted versus slit depth l for fixed width w=0.5 mm. The response of the dual-mode resonator for the port configuration shown in Fig.2b is identical to two coupled resonators with a capacitive coupling. As it follows from Fig.2c a rather wide range of coupling can be achieved for reasonable sizes of the slit. The final designing of the filter consist of simulations that involves Ansoft's ADS, HFSS, and Momentum. First, the lumped element equivalent circuit of the filter prototype is analyzed in ADS using measured susceptance slope parameter b. The inter-mode coupling coefficient obtained from this analysis is used in HFSS to select the dimensions of the slit (Fig.2c). Further, the equivalent

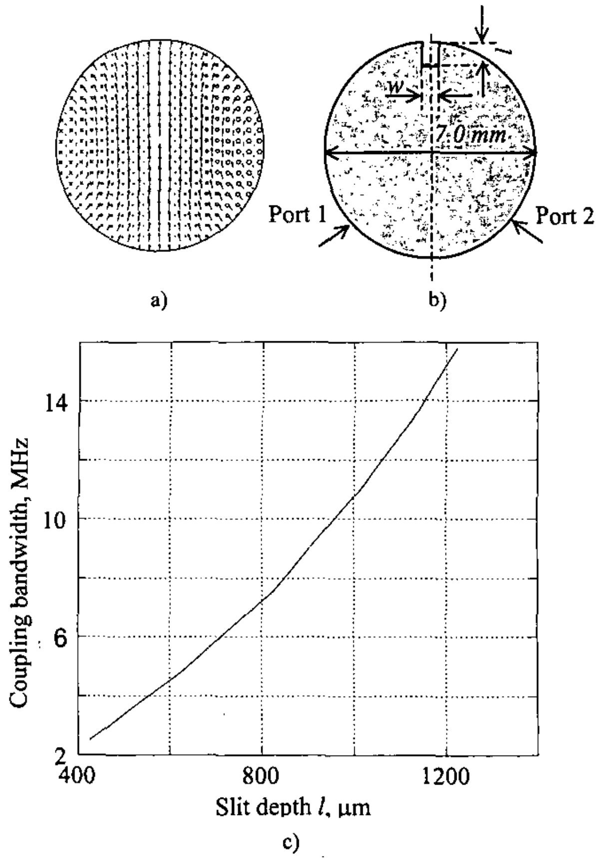
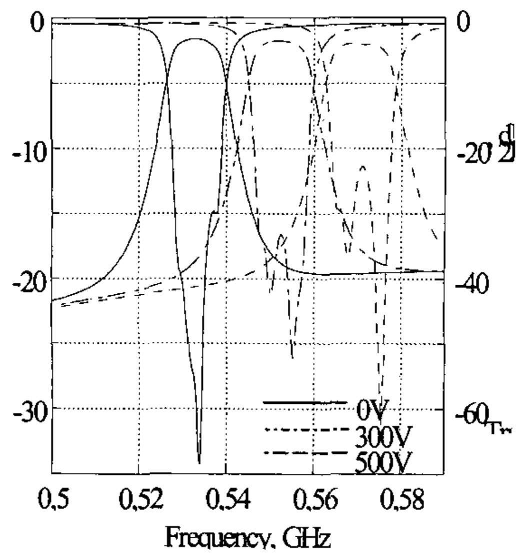


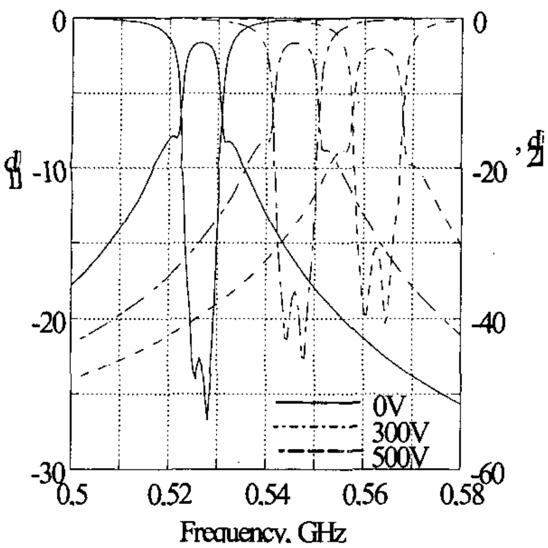
Fig.2 The magnetic (→) and electric (o and ×) field patterns of the TM_{110} mode (a), upper electrode with a perturbation slit (b), and coupling bandwidth versus slit depth l.

circuit parameters obtained in ADS are used in Momentum to develop the layout of the microstrip network of the filter. Finally, the S-parameters of the microstrip network from Momemtum simulation, and S-parameters of the dual mode resonators from HFSS simulation are exported to ADS circuit simulator to simulate the overall filter performance.

The simulation procedure described above is used to design two four-pole filters with 2% and 1.8% fractional pass-bands. The results of simulations, obtained after a number of simulation/optimization steps, are presented on Fig.3a, b. The final layouts of these filters are presented on Fig.4a, b. In the layouts, the input/output microstrip lines are symmetric with respect to the slit (see also Fig.1b). Shown in Fig.4a is the layout of a filter with Chebishev response, corresponding to performance depicted in Fig.3a. The open stub *3*, section of high impedance line *2* and a capacitance borrowed from the first resonator establish a π-network, which provides coupling with feed line *1*. The inter-disc or second-to-third resonator coupling is realized on the section of transmission line *5* and capacitances, which are borrowed from the second and third equivalent resonators. (They are the same as the one used in the discussed above π-network).



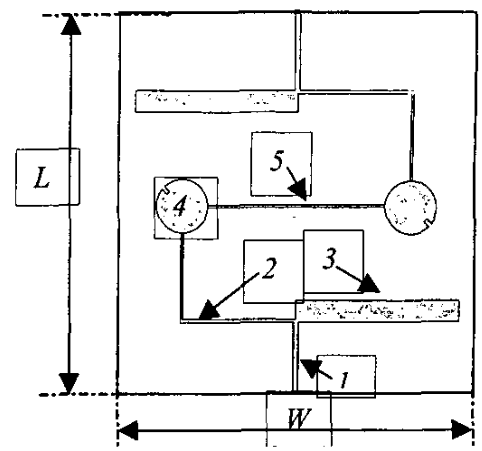
a)



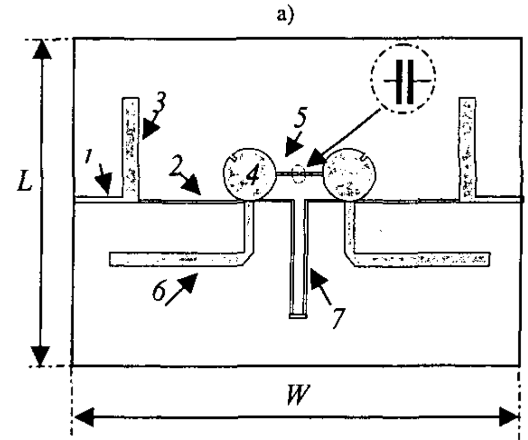
b)

Fig.3. Simulated response of filters with Chebishev response (a) and, with two transmission zeros (b).

The layout shown in Fig.4b is designed to get a response with transmission zeros symmetrically located at the low and high frequency skirts, as shown in Fig.3b. The microstrip open stub *6* is used to increase the equivalent capacitance of the first (fourth) resonators. The effect of this stub is equivalent to introducing a parallel negative capacitance at the end(s) of line section 5, which is required for the inter-disc capacitive coupling. For the same reason a lumped capacitance is inserted in a section of microstrip line *5*. The high impedance line section *7* establishes an inductive coupling between first and fourth resonators. In both filters we use 0.625μm thick "Duroid" substrate with via holes for the disc resonators. The dimensions of the filters are: *L*=*W*=40 mm (Fig.3a), *L*=36mm, *W*=76mm (Fig.3b).



a)



b)

Fig.4 Layouts of filters with Chebishev response (a), and with transmission zeros (b).

In the two filters discussed above the aim was to get maximum possible tunability at the expenses of somehow higher losses. However, in case the losses are critical issue one can use HTS electrodes and limit the tunability below 2%, corresponding to bias fields where the Q-factor is still high. Fig.5 shows the simulated filter performance for Q=1000. As it can be seen the losses (about 1.0 dB) are quite low, and a substantial improvement in the steepness of the skirt is available.

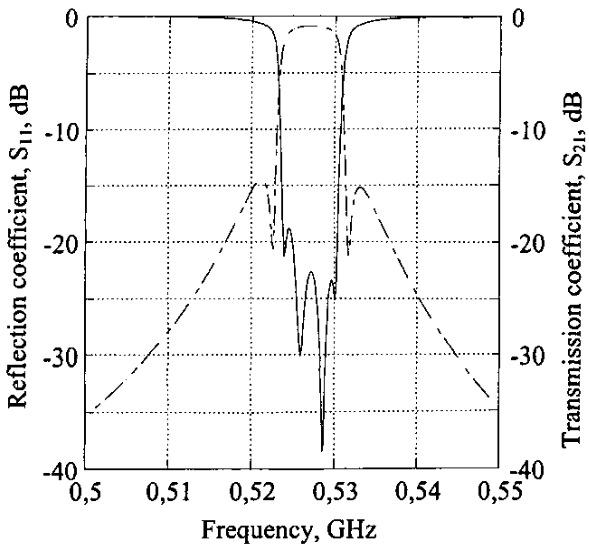


Fig.5 Filter performance with HTS electrodes (Q=1000).

III. CONCLUSION

Design of tunable band-pass filters on dual-mode parallel plate resonators based on combination of experiment, full wave and circuit analysis is presented. The results for two 0.5 GHz four-pole tunable filters based on two disc resonators are given. The insertion losses of the filters are limited by the losses in STO crystals. Introduction of the transmission zeros for the same number of disc resonators improve the steepness of the skirts. Filters with lower losses, smaller tuning ranges (<2%) and steeper skirts may be realized where HTS electrodes are used instead of copper. The filters advantageously compare with the commercial analogues [7]. The experiments, currently in progress, will be reported in a forthcoming publication.

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