# Full-wave modeling of HTS dual-mode patch filters and staggered coupled-line filters

A. Flores, C. Collado, C. Sans, J. O'Callaghan, R. Pous
Universitat Politècnica de Catalunya. Campus Nord-D3. Barcelona 08034, Spain.

J. Fontcuberta
ICMAB-CSIC. Campus UAB. Bellaterra 08913, Spain.

*Abstract*— In order to obtain high-power handling, dual-mode patch HTS filters have been analyzed through Green's function and desegmentation techniques. A precise circuit model has been obtained and applied to the filter design process, and useful design curves relating filter parameters and physical dimensions of the square patch have been plotted. Several designs have been made using them and then optimized with the Method of Moments in the Spectral Domain. For higher order circuits, staggered coupled-line HTS filters have been considered. The designs have been made using the method of moments to compute the coupling capacitances, and then optimized with the Method of Moments in the Spectral Domain. One dual-mode patch filter and one staggered coupled-line filter have been fabricated on a YBCO film. Measurements agree well with simulations.

*Keywords*— Superconductive devices, filters, modeling

## I. Introduction

THE use of HTS materials in the construction of passive filters limits sometimes their power-handling capability due to the critical current of the superconductor. This limitation can be partially overcome by using as much surface as possible in order to reduce the current density. However, a filter structure must also efficiently use the available surface so that high order filters can be designed using small area HTS films. The dual-mode patch filter has proved to be a useful filter structure for this purpose [1]. A square patch is cut in one of its corners so that both degenerate modes are coupled together and a second-order filter can be designed, Fig. 1. Even-order filters can be constructed by adding these dual-mode structures. Although some filters of this kind have been designed [2], an accurate circuit model must be found in order to design the filter. In this letter, the authors present a new analysis and a final design method and graphs. Simulations and measurements are also presented which agree with design characteristics.

A staggered coupled-line filter was published in [4] and is shown in Fig. 2. Here we present the results of applying the discussion and analysis of the structure to microstrip techniques, as well as some measurements and full-wave simulations through the Method of Moments in the Spectral Domain (MoM) [3].

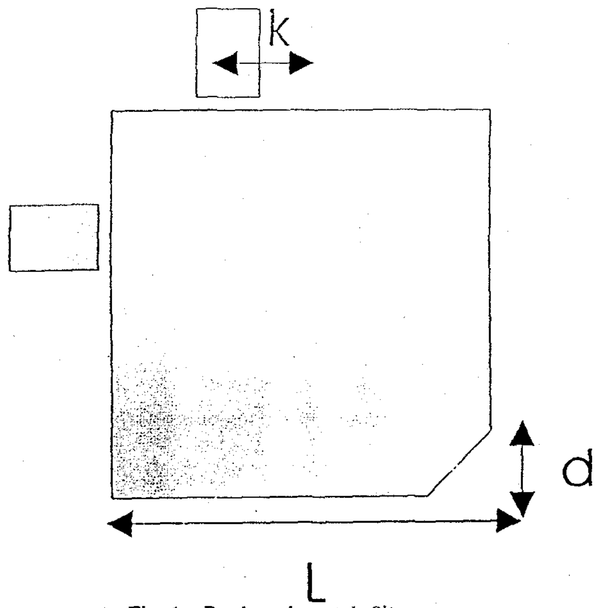


Fig. 1. Dual-mode patch filter

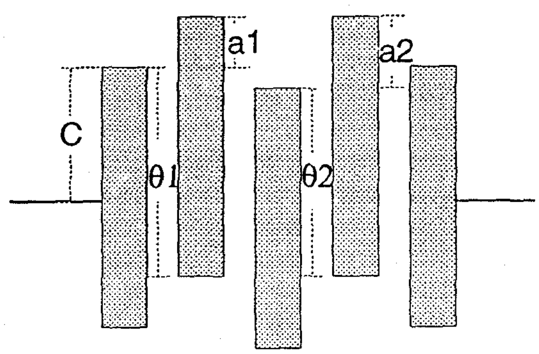


Fig. 2. Staggered coupled-line filter

## II. Analysis

Considering the corner-cut square as a planar microwave circuit, it is analyzed through desegmentation techniques [7]. This technique is based on the fact that a square can be considered as the sum of the structure under analysis and a isosceles triangle, so that their Z-matrices can be linearly combined. The Z-matrix of the patch can then be computed from the Z-matrices of a perfect square patch and a triangular patch, Fig. 3.

For these regular geometries, where we also approximate the electric field as having only one component and no vertical variation simplified Green's functions, may be used to obtain accurate results, thanks to their closed form [7]. These functions consider the mutual impedance between different locations of the ports, defined with a specific width. Therefore, the contour must be segmented. For this analysis the square has been segmented into 15 locations of the ports and the size of the triangle has ranged from 1 to 7 times the length of one of the segments of the square.

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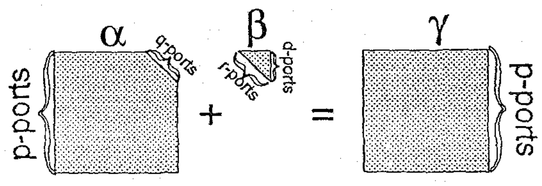


Fig. 3. Desegmentation of the structure

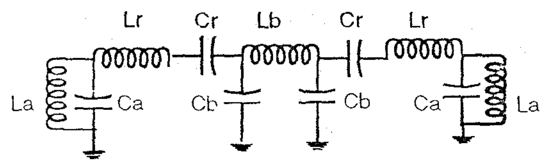


Fig. 4. Circuit model

Thus, although the equations consider different widths of the ports, in our case this parameter is constant and the process is simplified.

With the programmed segmentation-routines, the impedances between ports can be computed at different frequencies. The frequency dependence of the impedances and admittances have been observed in modulus and phase and a circuit model has been matched to them, suggested by physical considerations.

This model agrees with the physical structure because the two resonators correspond to the two degenerate modes coupled by an inductor as they share the same surface. It has the topology of a lumped-element 2-pole filter (since the resonant frequency of $L_a$ and $C_a$ is much higher than the band of interest). The elements considered allow us to construct a network with resonators and impedance inverters. Adjusting the values of the elements to correspond to different positions of the ports and different cut depths (defined as the side length of the triangle $\beta$ in Fig. 3), the characteristic parameters of the filter are associated to the physical dimensions. We find a rational expression that matches the form of $Y_{21}$ as a function of frequency in the minimum square sense. Then we solve the non-linear system that relates the lumped elements with the coefficients of the rational expression. The same process is followed with $Y_{11}$ for it gives information about the input parallel capacitance and inductor. Finally, the input capacitances are a basic element to obtain the desired ripple and bandwidth.

## III. Design graphs

Once a circuit model has been found and it has been interpreted as a second-order filter, the next step is to relate geometry to circuit values. The impedance inverters values must be associated with the different positions of input and output ports, cut depths and the sidelength. These three plots are shown in Figs. 5, 6 and 7.

All measures are plotted in percentages of the sidelength. Labeling the bandwidth as $BW$ and $g_1$, $g_2$ as the normalized immittances of the low-pass prototype response, the first plot shows the value of $\frac{BW^2}{g_1 \cdot \sqrt{g_1 \cdot g_2}}$ that does not change

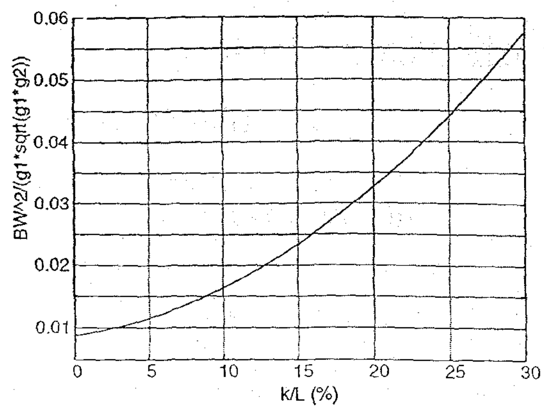


Fig. 5. Plotting parameters 1

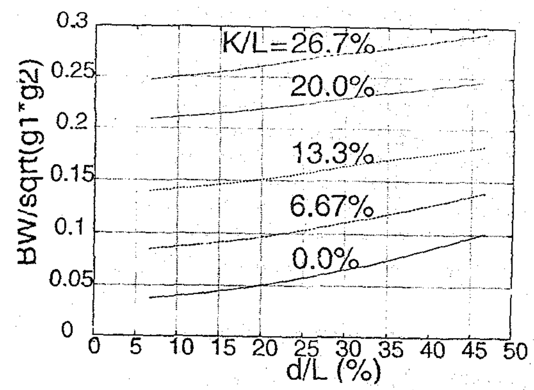


Fig. 6. Plotting the 2nd parameters

for different cut depths, so that the location of the ports can be fixed independently. The second plot allows the designer to fix the cut depth depending on the value of $\frac{BW}{\sqrt{g_1 \cdot g_2}}$ and the deviation of the ports from the center and towards the corner that is not cut (K in Fig. 1). The third plot is the deviation from the designed central frequency due to the cut depth.

## IV. Design method

Using these plots, a validated design method has been established. The steps in dual-mode filter design are:

1.- Define the prototype from the normalized immittances,

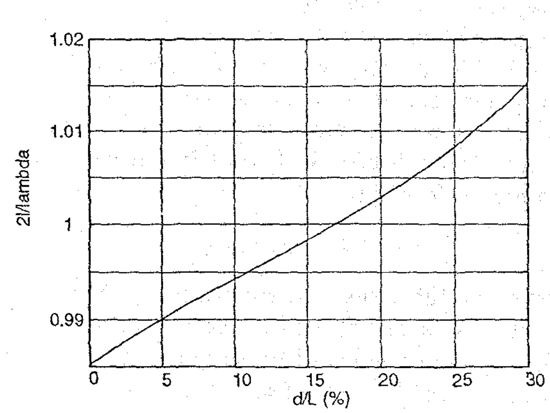


Fig. 7. Plotting the 3rd parameters (lambda is the wavelength)

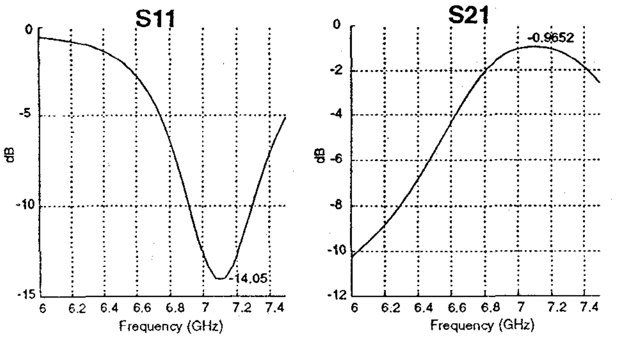


Fig. 8. Simulation without input capacitance and substrate height of 0.635mm

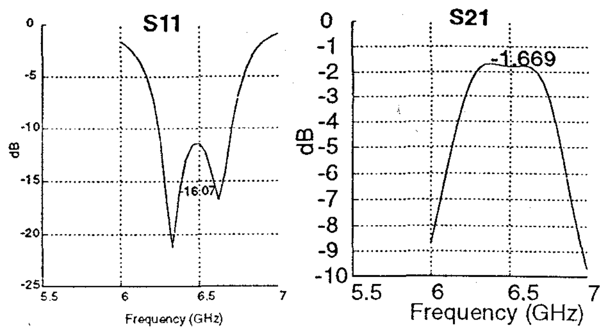


Fig. 9. Simulation with input capacitance and substrate height of 1mm

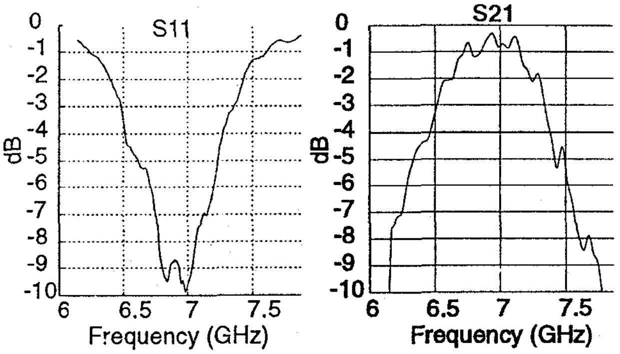


Fig. 10. Measurement of the superconductive dual filter

bandwidth and ripple and the values of inverters needed $K_{01}$ and $K_{12}$ [8].

2.- Fix the position of the ports with Fig. 5

3.- Once the position of the ports is fixed, establish the cut depth in % of the sidelength from Fig. 6

4.- In Fig. 7 look up the central frequency deviation factor. This does not include the fringing effect. Establish the square's sidelength so that it is $\lambda_{ef}/2$.

5.- Optimize the design with MoM simulations

## V. Examples of design

Using these plots and following the design method, two different designs were done. Simulations by the MoM in the Spectral Domain showed a close similitude to the original parameter. The design specifications were: 6% bandwidth and 0.1 dB-ripple, and 10% bandwidth and 1 dB-ripple. The simulations resulted in 6.5% and 11% respectively. The input capacitance was designed with an interdigital structure since its value was too high to be achieved with a simple gap. Then, two prototypes were optimized from the design with 6% bandwidth, with different substrate thickness. This is a factor that influences in the input capacitance. In the thinner case the required input capacitance was judged to be so high and so difficult to construct that not much was lost if it was substituted with a short circuit (the effect of neglecting the series input capacitance is shown in Fig. 8, compared to Fig. 9). With the thicker substrate the required capactiance corresponded to a gap of only $50\mu m$. Radiation losses had been previously and qualitatively considered but they were reduced by the placement of the circuit inside of a closed brass box.

Finally, a superconductive dual filter was constructed with a YBCuO layer on a 1mm thick MgO substrate according to the 6% bandwidth design. The simulations and measurements for the design with and without the input capacitance are shown in Figs. 8 to 10:

Because the input capacitance is designed as an interdigital capacitance, the initial geometry is partly modified and central frequency is lower, although simulations show a greater shift than measurements. It can also be seen that although the simulations consider radiation (they are included in the MoM software used), the losses in measurements are lower for the circuit is inside a brass box.

## VI. Staggered coupled-line filter

The structure shown in Fig. 2 allows us to design very narrow bandwidth microwave filters, although there are limitations in power handling. The analysis was first presented in [4] as a novel resonator array filter, adapted to the microstrip case. This leads to a formulation that is slightly different, because the even and odd modes produce different phase velocities. The electrical dimensions in both cases are therefore also different. Considering the filter as a two-port structure, the admitances are:

$$\mathrm{Y}_{21} = Y_{12} = (2 \cdot j \cdot (Z_{0e} \cdot \csc\theta_k^e - Z_{0o} \cdot \csc\theta_k^o)) \,/\, (Z_{0e}^2 + Z_{0o}^2 - 2 \cdot Z_{0e} \cdot Z_{0o} \cdot (\cot\theta_k^e \cdot \cot\theta_k^o + \csc\theta_k^e \cdot \csc\theta_k^o)) \tag{1}$$

$$\mathrm{Y}_{11} = Y_{22} = (-2 \cdot j \cdot (Z_{0e} \cdot \cot\theta_k^e + Z_{0o} \cdot \cot\theta_k^o)) \,/\, (Z_{0e}^2 + Z_{0o}^2 - 2 \cdot Z_{0e} \cdot Z_{0o} \cdot (\cot\theta_k^e \cdot \cot\theta_k^o + \csc\theta_k^e \cdot \csc\theta_k^o)) \tag{2}$$

Now, identifying the $\Pi$ circuit of a biport with a filter structure with admitance inverters and shunt resonators, Fig. 12, we have:

$$\mathrm{J}_{k,k+1} = |2 \cdot j \cdot (Z_{0e} \cdot \csc\theta_k^e - Z_{0o} \cdot \csc\theta_k^o) / (Z_{0e}^2 + Z_{0o}^2 - 2 \cdot Z_{0e} \cdot Z_{0o} \cdot (\cot\theta_k^e \cdot \cot\theta_k^o + \csc\theta_k^e \cdot \csc\theta_k^o))| \tag{3}$$

and

(4)

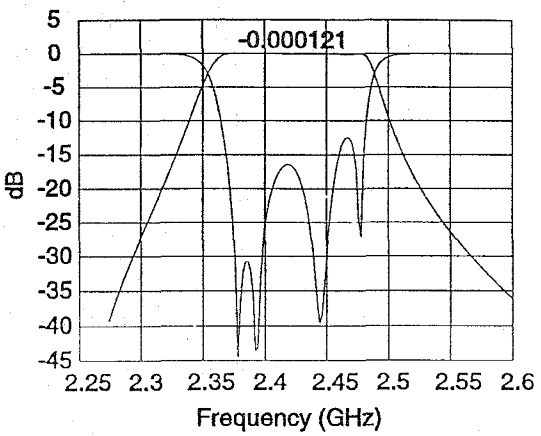


Fig. 11. Simulation of the fifth order staggered coupled-line filter

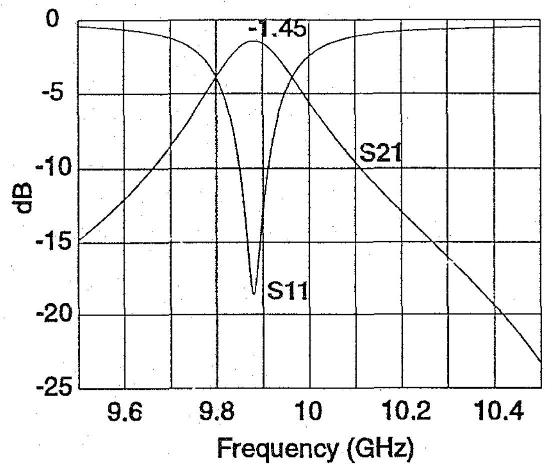


Fig. 12. Simulation of the third order staggered coupled-line filter

$$B_k = (-2 \cdot j \cdot (Z_{0e} \cdot \cot\theta_k^e + Z_{0o} \cdot \cot\theta_k^o)) \, / \, (Z_{0e}^2 + Z_{0o}^2 - 2 \cdot Z_{0e} \cdot Z_{0o} \cdot \cot(\theta_k^e \cdot \cot\theta_k^o + \csc\theta_k^e \cdot \csc\theta_k^o)) + + \frac{a \cdot \sqrt{\theta_k^e \cdot \theta_k^o}}{Z_k}$$

The impedances for both even and odd modes are computed from the numerically-simulated capacitances of a multiconductor structure, which are given by the software published in [9]. The initial values of the respective lengths are later optimized in simulations using the Method of Moments in the Spectral Domain.

## VII. Examples of staggered coupled-line filters. Measurements

Using the above equations, different designs were undertaken for third and fifth order filters. The simulated responses are shown in Figs. 11 and 12. A prototype on superconductive YBCuO layer and was later measured, and exhibited a response similar to the predicted performance. We present the result in Fig. 13.

## VIII. Conclusions

In this paper we have presented two structures that have proved to behave as valid microwave filters. For the dual-mode patch filter, we have presented an analysis procedure, a circuit model and a design method. Measurements and

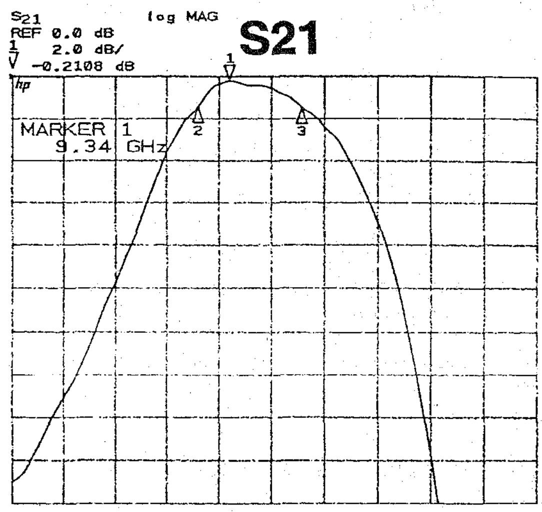


Fig. 13. Measurement of the superconductive Staggered coupled-line filter

Method of Moments simulations have proven the method and design graphs to be valid. Dual-mode patch filter design has therefore been systematized and higher order filters can be implemented. For the staggered coupled-line filters, we have taken existing analysis and translated it into the non-homogeneous case (i.e. microstrip). Measurements and MoM simulations also agree with the design method.

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