Design of a superconducting antenna integrated with a diplexer for radio-astronomy applications.

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***Abstract*—The design of a compact front-end diplexer for radio-astronomy applications was done with a self complementary bowtie antenna, a 3dB T-junction splitter and two pass-band fractal filters. The diplexer structure has been optimized by using an evolutionary algorithm, namely the Particle Swarm Optimization (PSO). The optimization is done by minimizing a suitable cost function that represents the difference between the diplexer requirements and the performance obtained by a set of randomly generated trial solutions. An X-band scale model prototype of the final diplexer in the 10 and 14.66 GHz frequency bands was fabricated and tested. A good agreement was found between numerical and experimental results.**

I. Introduction

In the last years there has been a growing demand of wireless services that has led to an overexploitation of the available radio frequency resources in terms of channels and frequency bands availability. This has forced researchers to find strategies to protect the frequency bands typically used for radio-astronomy applications by introducing suitable filters able to remove or strongly reduce interference signals, while keeping at the same time the integrity of the weak signals received by the radio-telescopes. Moreover it is necessary to limit the bandwidth to the frequency range of interest to minimise the external noise received by the detector. In this frame it is mandatory to use filters characterized by a high selectivity and low losses: this can be easily accomplished with circuits based on superconducting materials. Most of time low critical temperature superconductors (LTS) are used for the detector and its surrounding circuitry, that are both cooled at, or below, the temperature of liquid helium. High critical temperature superconductors (HTS) can also be used in the THz range, when the frequency is above the gap frequency of LTS [1] since, in this frequency range, typically above 700 GHz for niobium, LTS exhibit too many losses for sensitive detection. On the other hand the design of superconducting passive devices can be first obtained by considering copper microstrip structures and commercial dielectric material with the goal of testing the design methodology at room temperature before moving toward a cryogenic design. With such an approach, one has to keep in mind that, for a given geometry and physical parameters like the dielectric constant of the substrate and insulating layers, the kinetic inductance of superconducting films [2] is not properly taken into account, which results in different propagation velocity and characteristic impedance of transmission lines. This effect is particularly significant for thin film microstrip designs, while, most of time, coplanar designs give closer results between normal metal and superconducting films designs [3]. The use of a superconducting diplexer equipped with efficient antennas and filters able to select simultaneously two or more frequency bands of the signal is of interest for Cosmic Microwave Background (CMB) observations relying on the spectral modification of the Planck law by the Sunayev-Zeldovich (SZ) effect [4]. Self-complementary bowtie antennas [5] seem to be appropriate candidates for achieving good performances since their use, combined with fractal geometries for filters, has been proven very efficient to achieve miniaturization, enhanced bandwidth and good performances [6], [7]. Indeed, the miniaturization of the antenna front-end is important for future multi-pixel microwave receivers based on imaging arrays. The proposed compact broadband diplexer is a complex system, and conventional microwave design techniques are quite effective only for the design of basic microwave active as well as passive devices [10]-[13], but these techniques are not able to models the interactions between the different components of complex systems with efficacy, usually a final tuning that could dramatically increase the costs of the device, and increase the number of design/fabrication cycles, is mandatory to obtain working devices. In last years microwave CAD tools [14]-[16] have been proposed for the design of complex microwave systems, have been successfully adopted in many areas of applied electromagnetism such as antenna design [17]-[18], control [19] and other interesting applications [20]-[24]. In fact, these tools can analyse, design and modify, microwave devices in an unsupervised manner. Certainly they can't completely replace an experienced microwave engineer but they can offer a precious help the designer to strongly reduce the time necessary to design complex microwave systems. In these tools, the design problem is usually recast as an optimization problem that can be handled by means of a suitable optimization algorithm and a suitable cost function. The latter represents the distance between the required performances and the obtained trial solution. These design tools usually consist of an optimizer and a commercial numerical simulator, and in recent years they have been integrated into commercial microwave simulators. This work presents the optimized synthesis [8] of a superconducting diplexer based on a broadband self-complementary bowtie antenna and two fractal passband filters that operate at two frequency bands centered at 10 and 14.66 GHz respectively. The optimization of the receiving structure is carried out considering a numerical procedure based on a PSO algorithm [9]. The key of force of this method is that it takes into account the different interactions and coupling phenomena, always present when a complex microwave system or circuit is developed. At the end of the optimization procedure the proposed method provides, not only the design of the single devices of the diplexer but a complete systems where the requirements of each microwave component namely the antenna, the filters and the splitters respect the initial system requirements. An experimental prototype has been designed, fabricated and assessed experimentally.

II. Synthesis of the diplexer structure

The receiving diplexer structure under consideration consists of a self-complementary bowtie antenna, a 3dB T-junction splitter and two bandpass filters based on fractal resonators. The T-junction and the two filters implement a three-port diplexer. The design has been formulated as an optimization problem fixing suitable constraints in terms of impedance matching at the input port ($|S_{11}|$ values). Moreover the two output ports of the diplexer will be connected to a power meter with an input impedance of $Z_{in} = 200\Omega$ with $|S_{11}| < -10dB$; the two frequency bands are respectively centered at $10GHz$ and $14.66GHz$ with a bandwidth of about $100MHz$ each. The design is based on microstrip technology. The geometrical parameters reported in Fig.1 permit to simultaneously maximize the performance and minimize the size of the antenna and of the fractal resonators. In particular the diplexer structure is uniquely determined by the following vector $\underline{\Gamma} = \{H_i, i = 1, \cdots 7; S_j, j = 1, \cdots 6; t_k, k = 1, \cdots 4, D\}$ that describes the geometrical parameters of the diplexer of Fig.1. To meet the objectives, a cost function, that represents the difference between the requirements and the performances of a trial diplexer geometry, is defined by:

$$\Phi\left\{\underline{\Gamma}\right\} = \sum_{h=1}^{H} max\left\{0; \frac{\Psi\left(h\Delta f\right) - |S_{nn}|_{max}}{|S_{nn}|_{max}}\right\} \qquad (1)$$

n indicates the port number, Δf is the frequency step in the range between 8 and 15 GHz and the function $\Psi\left(h\Delta f\right)$ is the $|S_{11}|$ at the frequency $h\Delta f$ when the trial geometry defined by the $\underline{\Gamma}$ vector is considered, and $|S_{11}|_{req}$ represents the return loss requirement in dB. To minimize (1) a suitable version of the PSO has been used, in combination with a geometrical generator and a commercial electromagnetic simulator (namely HFSS designer), to estimate the characteristics of the trial diplexer geometries. In particular the minimization of (1) is obtained by constructing a sequence of trial solutions $\underline{\Gamma}_s^k$ (s being the trial solution index, and k the iteration index $k = 1, \ldots, K_{max}$) following the strategy of the PSO. The iterative optimization algorithm continues until the stopping criteria are reached, in particular when $k = K_{max}$ or $\Phi\left(\underline{\Gamma}_s^k\right) < \beta$, where K_{max} and β are respectively the maximum number of iterations and a convergence threshold. At the end of the iterative procedure the optimal solution defined as $\underline{\Gamma}^{opt} = arg\left\{min\left[\Phi\left(\Gamma_k\right)\right]\right\}$ is stored and the obtained geometrical parameters are used to fabricate the diplexer prototype.

TABLE I: Diplexer, geometrical parameters obtained at the end of the PSO optimization procedure. All dimensions are in [mm].

t_1	t_2	S_1	H_1	D	$S_{1,4}$	H_4	$H_{5,7}$
0.8	2.0	10.0	7.1	15.0	1.0	7.0	9.0

III. Numerical and Experimental assessment

To obtain a diplexer prototype the cost function (1) is minimized according to the guidelines given in [], and a suitable implementation of the PSO [19] has been used in conjunction with a circuital generator, and a microwave circuital simulator able to take into account all the interactions between all subsystems. Starting from each of the trial arrays Γ the PSO, the circuital generator changes the geometrical parameters of each sub-system and then it generates the corresponding system structure. The performance of the whole system, are computed by means of a circuital simulator, which take into account the presence of dielectric substrate, the mutual coupling effects between all the subsystems, and it is used to estimate the cost function (1). The iterative process continues until $k = K_{max}$ or when a convergence threshold on the cost function (1) is reached. Then the array Γ, that contains the geometrical parameter that define the diplexer geometrical structure is stored and used for the development of the prototype. At the beginning of the iterative optimization procedure based on the PSO optimizer, a set of $S = 10$ trial geometrical parameters are randomly initialized and used as starting point for the optimizer. Concerning the specific PSO parameters a population of $S = 10$ individuals, a threshold of $\beta = 10^{-3}$ and a maximum number of iterations $K_{max} = 100$, and a constant inertial weight $\beta = 0.4$ were used. The remaining PSO parameters have been chosen according to the reference literature [8], [9]. A geometry generator generates a set of trial diplexer geometries that are estimated by means of an electromagnetic simulator, which take into account the presence of the dielectric substrate. Then the cost function (1) is evaluated and, thanks to the PSO strategy, the swarm evolves improving their characteristics. The iterative procedure continues until the maximum number of iterations or the threshold on the cost function is reached. As an illustrative example of the optimization process, Fig. 2 shows the behaviour of the cost function versus the iteration number during the optimization of the diplexer geometry. As it can be noticed from Fig. 2, the algorithm end when the maximum number of iteration fixed to $K_{max} = 100$ is reached. A prototype has been fabricated with a milling machine using a dielectric substrate of thickness $t = 0.8$, $\varepsilon_r = 3.28$ and $tan(\delta) = 0.003$. The photo of the bottom side of the prototype is displayed in Fig.3. The following geometrical parameters have been considered, $t_1 = 0.8mm, t_2 = 2mm, S_1 = 10mm, H_1 = 7.1mm, D = 15mm, S_3 = S_4 = S_5 = S_6 = 1mm, H_5 = H_6 = H_7 = 1mm, , H_4 = 7mm, and H_5 = 9mm$. The geometrical parameters related to the diplexer are also summarized in Tab. I.

Concerning the fractal resonators are made considering the second iteration of the Koch fractal algorithm. Due to mechanical constraints it was not possible to further reduce the dimensions of the resonators by increasing the number of

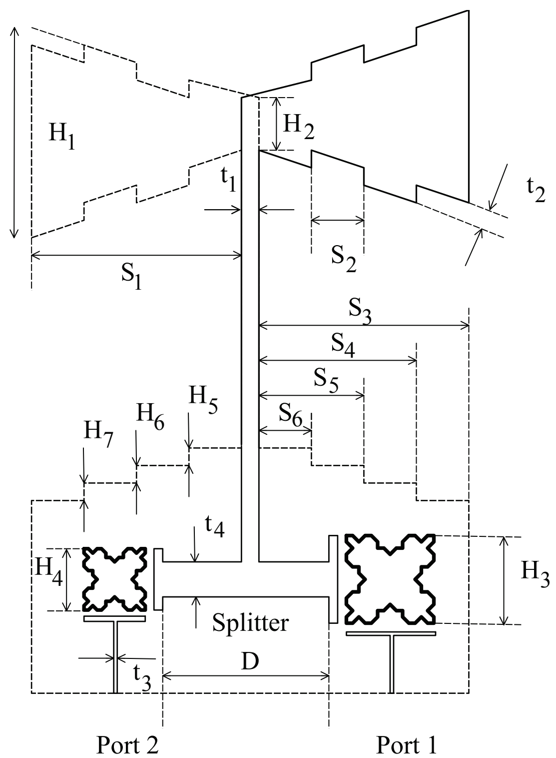

Fig. 1: Geometry of the diplexer structure under study.

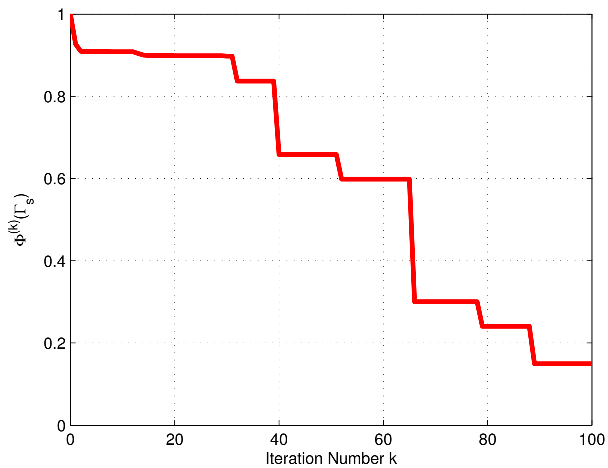

Fig. 2: Behaviour of the cost function versus iteration number k.

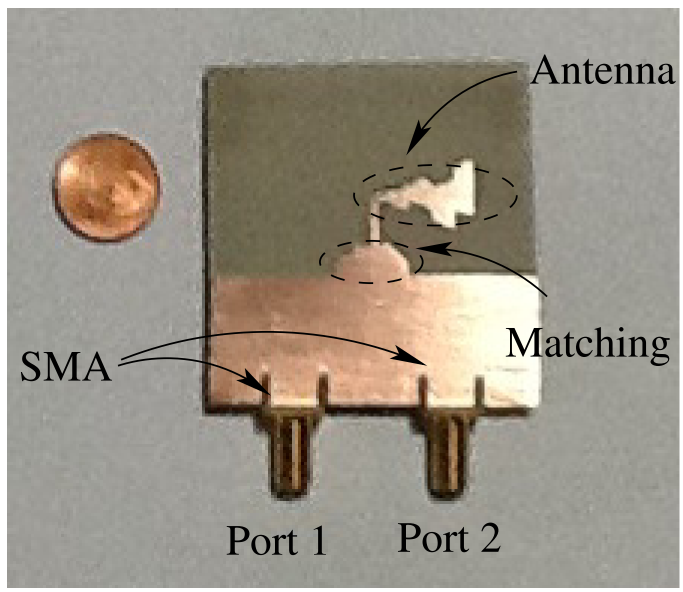

Fig. 3: Picture of the bottom side of the fabricated diplexer prototype, with dimensions obtained at the end of the PSO optimization.

fractal iterations. The fabricated prototype has been equipped with two sub-miniature type A (SMA) coaxial connectors. An experimental setup has been arranged inside an anechoic chamber to assess the characteristics of the prototype: the $|S_{nn}|$ parameters were measured at both ports with a network analyzer. As can be noticed in Fig.4 the obtained results meet the initial requirements: the return loss for the two considered frequency bands is found to be below the initial requirements by about 5 dB at center frequencies. To be more extensive, the measurements have been compared with numerical data obtained with the HFSS commercial software, which has been able to accurately simulate the considered structure, since the agreement between numerical and experimental data is quite good, as can be seen in Figs.4 *a* and *b*. In particular in the two bands of interest the S_{nn} keeps below -10 dB for the whole range of interest, and the lowest values obtained for the S_{nn} is below -15 dB

IV. Conclusion

In this work the design of a receiving front-end scale model for radio-astronomy applications has been described. The receiver is composed of a broadband self-complementary bowtie antenna and a diplexer composed by a 3dB splitter and two band pass filters. The whole structure has been optimized through a particle swarm algorithm able to act on the geometrical parameters of the bow tie self-complementary antenna and of the two passband fractal filters, to comply with the impedance matching constraints. A prototype has been designed, based on microstrip technology, fabricated and experimentally assessed. The comparison between measured and numerical data demonstrate the effectiveness of the proposed design methodology and the potentialities of the proposed front-end structure. The next step will be to scale this design at millimeter wavelengths and include the superconducting properties of the films in the microwave simulations to estimate the final compactness and performance of the design for future microwave imaging systems.

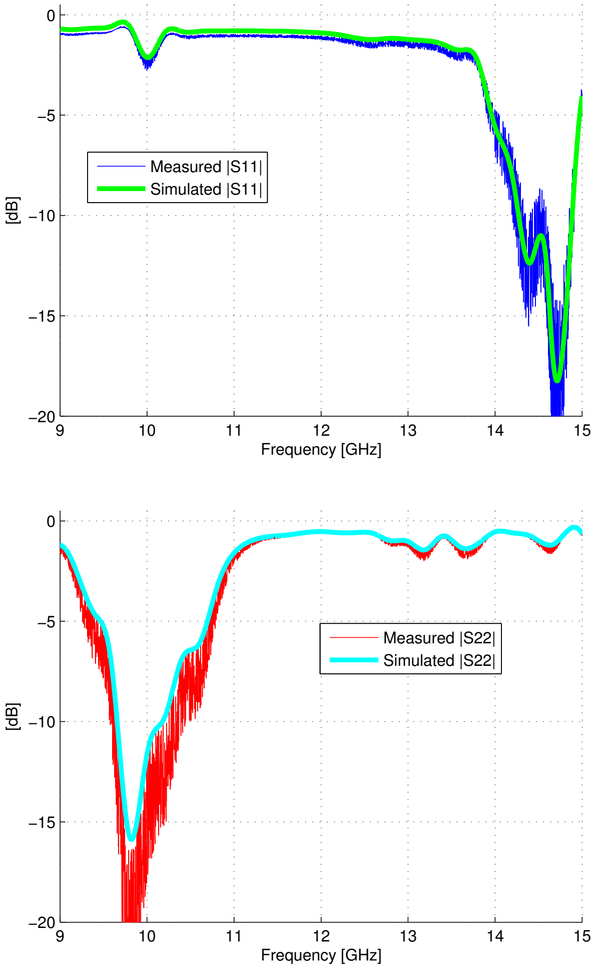

Fig. 4: Behaviour of S parameters at the two ports versus frequency. Comparison between numerical and experimental data.(*a*) return-loss S_{11} at port one, and (*b*) S_{22} at port two.

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