Paper

Design of a Superconducting Antenna Integrated with a Diplexer for Radio-Astronomy Applications

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Abstract—This paper presents the design of a compact front-end diplexer for radio-astronomy applications based on a self complementary Bow-tie antenna, a 3 dB T-junction splitter and two pass-band fractal filters. The whole diplexer structure has been optimized by using an evolutionary algorithm. In particular the problem of the diplexer design is recast into an optimization one by defining a suitable cost function which is then minimized by mean of an evolutionary algorithm namely the Particle Swarm Optimization (PSO). An X band diplexer prototype was fabricated and assessed demonstrating a good agreement between numerical and experimental results.

Keywords—diplexer, microwave antenna, optimization techniques, particle swarm algorithm, radio-astronomy.

1. 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 weak signals integrity received by the radio-telescopes. Moreover it is necessary to limit the bandwidth to the frequency range of interest to minimize 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 [8]–[11]. 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 [12]–[14] have been proposed for the design of complex microwave systems, have been successfully adopted in many areas of applied electromagnetism such as antenna design [15]–[16], control [17] and other interesting applications [18]–[22]. 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 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 [23] of a superconducting diplexer based on a broadband self-complementary Bow-tie 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 [24]. 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.

The paper is organized as follows. Section 2 reports a detailed description of the proposed superconducting broadband antenna integrated with the diplexer structure. Section 3 summarize the optimization procedure based on the particle swarm optimizer (PSO) adopted for the design of the diplexer structure. In Section 4 an experimental diplexer prototype, obtained with the design procedure described in Section 3, will be designed, fabricated and experimentally assessed. Finally in Section 5, conclusions are drawn and areas for future works are examined.

2. Superconducting Antenna and Diplexer Structure

The receiving diplexer structure proposed in this work is reported in Fig. 1, it consists of a self-complementary Bow-tie antenna [5], a 3 dB T-junction splitter and two bandpass filters based on fractal resonators. The T-junction and the two filters, implement a two-ports diplexer. The proposed microwave system must be able to receive an incoming electromagnetic signals in a frequency band between 9 and 15 GHz, to reach this goal a broad band antenna is mandatory, in particular in this work a self complementary Bow-tie antenna is considered. The main advantage of a self-complementary antenna is the constant impedance independent of the source frequency. In particular the input impedance of a self complementary antenna is given by the well known Mushiake formula $Z_a = Z_m/2$ where Z_a is the antenna impedance, and Z_m is the intrinsic impedance of the medium. As it can be noticed from the Fig. 1, the incident electromagnetic wave impinges on the self-complementary antenna and it is equally splitted by means of a 3 dB T-junction microstrip power splitter [8]. A T- junction 3 dB power splitter has been chosen because it is a lossless and broadband device. Half of the signal power travels on the left side of the circuit and it is filtered by the first band-pass fractal filter which presents a band-pass frequency band centered at 14 GHz, then the signal leaves port 1 providing the first channel. The other half power of the signal is delivered toward the second fractal filter, characterized by a band-pass frequency band centered at 10 GHz, and after the filtering it leaves port 2. Both filters present a bandwidth of about 100 MHz. The use of fractal filters permits to strongly reduce the dimensions of the diplexer structure, fractals geometries demonstrated their effectiveness in the design of microwave antennas as in [25]–[27]. In particular a reduction of about $\frac{1}{3}$ has been obtained with respect to standard rectangular or circular resonators based pass-band filters. The two output channels of the diplexer must be connected with two power meters characterized with an input impedance of 200 Ω, and to guarantee a perfect match with a $S_{11} < -10$ dB between the ports of the diplexer, the coplanar microstrip waveguide which connect the antenna, and the 3 dB T-junction power splitter a multi-section broadband transformer has been considered [8]. In the next section the proposed design methodology based on the PSO algorithm will be detailed.

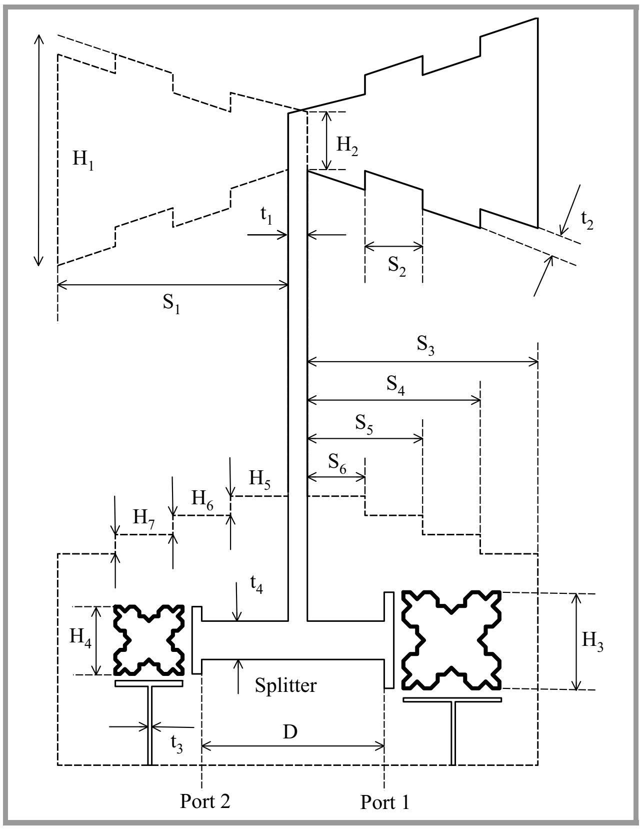

Fig. 1. Geometry of the diplexer structure under study.

3. Design Methodology Based on the PSO Algorithm

The PSO is a powerful multiple-agents optimization algorithm developed by Kennedy and Eberhart [20] in 1995 that imitates the social behavior of groups of insects and animals such as swarms of bees, flocks of birds, and shoals of fish. PSO has been used to solve complex antenna design and electromagnetic problems [28], [29]. The standard PSO implementation considers a swarm of trial solutions (called particles). Each particle travels in the solution space by improving its position according to suitable updating equations, on the basis of information on each particle's previous best performance (cognitive knowledge) and the best previous performance of its neighbors (social knowledge). For real-number spaces, the trajectories of the particles are defined as changes in the positions on some number of dimensions. With respect to other evolutionary algorithms such as genetic algorithms (GAs) the PSO shows indisputable advantages in particular. The PSO is simpler, both in formulation and computer implementation, than the GA, which considers three-genetic operators (the selection, the crossover, and the mutation). PSO considers only one simple operator, called velocity updating equation. PSO allows an easier calibration of its parameters and, in general, a standard configuration turns out to be adequate for a large class of problems and problem sizes. Consequently there is no need to perform a PSO calibration for every design experiment. PSO has a flexible and well-balanced mechanism to enhance the global (i.e., the exploration capability) and the local (i.e., the exploitation capability) exploration of the search space. Such a feature allows one to overcome the premature convergence (or stagnation) typical of GAs and it enhances the search capability of the optimizer. PSO requires a very small population size, which turns out in a reduced computational cost of the overall minimization by allowing a reasonable compromise between the computational burden and the minimization reliability. The antenna/diplexer system 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 $|S_{11}| < -10$ dB. The two frequency bands are respectively centered at 10 GHz and 14.66 GHz with a bandwidth of about 100 MHz each. The design is based on microstrip technology. The geometrical parameters shown in Fig. 1 permit to simultaneously maximize the performance and minimize the antenna size and of the fractal resonators. In particular the diplexer structure is uniquely determined by the following vector $\underline{\Gamma} = \{H_i, i = 1, \dots 7;\ S_j, j = 1, \dots 6;\ t_k, k = 1, \dots 4, D\}$ that describes the geometrical diplexer parameters (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:

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

where n indicates the port number, Δf is the frequency step in the range between 8 and 15 GHz and the function $\Psi(h\Delta f)$ 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 Eq. (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 Eq. (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 $k = 1, \dots, K_{\max}$) 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 $\underline{\Gamma}^{opt} = \arg\{\min[\Phi(\Gamma_k)]\}$ is stored and the obtained geometrical parameters are used to fabricate the diplexer prototype.

4. Numerical and Experimental Assessment

To obtain a diplexer prototype (Fig. 2) the cost function given by Eq. (1) is minimized according to the guidelines given in [24], and a suitable implementation of the PSO [17] 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

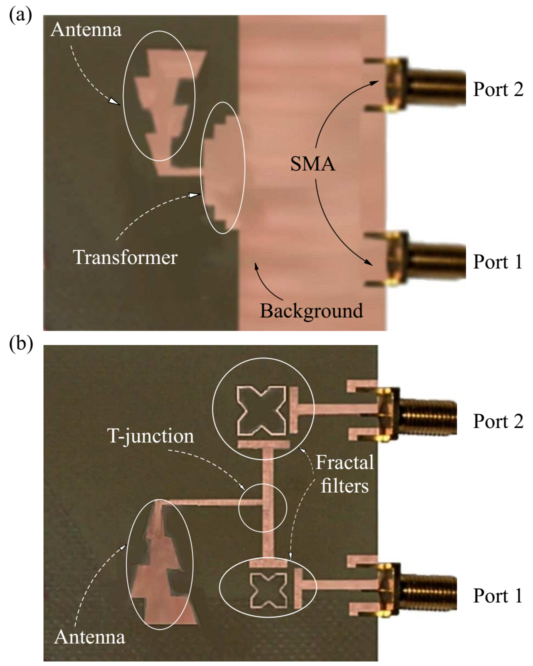

Fig. 2. Photo of the obtained diplexer prototype: (a) top view, and (b) bottom view.

structure. The whole system performance is 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 is reached. Then the array Γ, that contains the geometrical parameter that define the antenna and diplexer geometrical structure is stored and used for the prototype development. 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 [23], [24]. 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 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. 3 shows the behavior of the cost function versus the iteration number during the optimization of the diplexer geometry. As it can be noticed from Fig. 3, the algorithm end when the maximum number of iteration fixed to $K_{\max} = 100$ is reached. Concerning the computational burden required to accomplish the design of the diplexer, each iteration requires about 60 seconds on a serial machine equipped with 8 gigabytes of memory and four cores processor. The whole design procedure requires about two hours. It is worth noticed that thanks to the intrinsic capabilities of PSO parallelization it is possible to strongly reduces the computational time considering the same techniques proposed in [30], [31]. A diplexer 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 following geometrical parameters have been considered, $t_1 = 0.8$ mm, $t_2 = 2$ mm, $S_1 = 10$ mm, $H_1 = 7.1$ mm, $D = 15$ mm, $S_3 = S_4 = S_5 = S_6 = 1$ mm, $H_5 = H_6 = H_7 = 1$ mm, $H_4 = 7$ mm, and $H_5 = 9$ mm. 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 fractal iterations. The photo of the top and bottom side of the prototype is displayed in

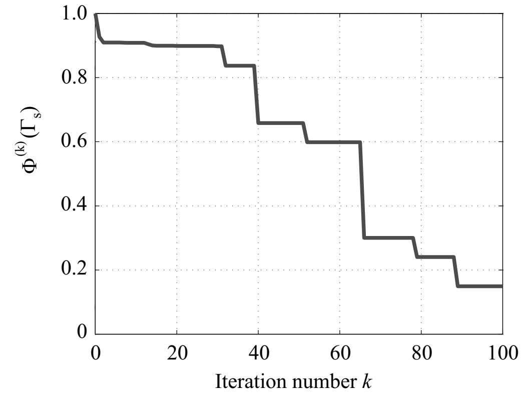

Fig. 3. Behavior of the cost function versus iteration number k.

Fig. 4. Experimental set-up. Photograph shows the anechoic chamber used for the experimental assessment of the diplexer prototype.

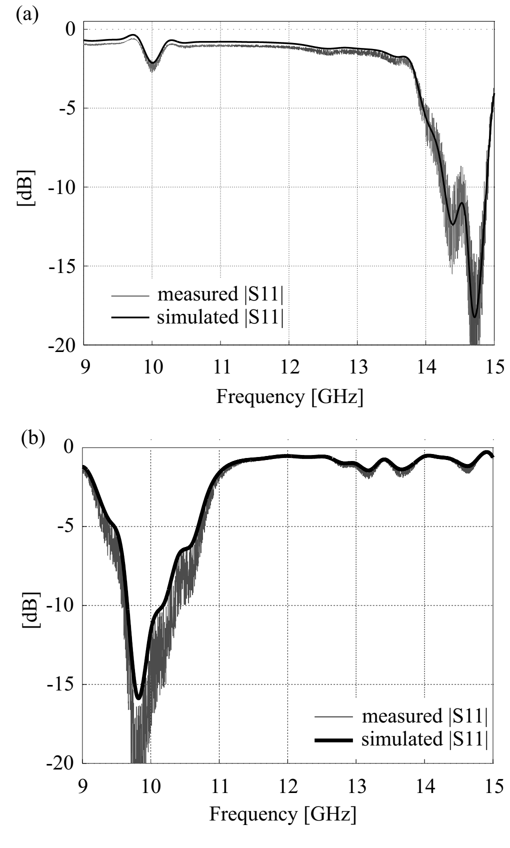

Fig. 5. Behavior of S parameters at the two ports versus frequency. Comparison between numerical and experimental data: (a) return-loss S_{11} at port one, and (b) S_{22} at port two.

Fig. 2. 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. The photo of the considered experimental setup arranged inside the anechoic chamber is shown in Fig. 4. The obtained results are reported in Fig. 5. As it can be noticed the obtained results meet the initial requirements: in particular the return loss for the two considered frequency bands is found to be below the initial requirements by about 5 dB at center frequencies. For the sake of comparisons, the measurements have been compared with numerical data obtained with the HFSS software, which has been able to accurately simulate the considered structure, the agreement between numerical and experimental data is quite good, as can be seen in Fig. 5. 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.

5. 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 Bow-tie antenna and a diplexer composed by a 3 dB 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 design performance for future microwave imaging systems.

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