Particle Swarm Algorithm Applied to Quadrature Hybrid Multi-Branch Directional Coupler Optimization for ALMA Band 3

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Abstract—**We introduce a novel optimization method based on the evolutionary algorithm Particle Swarm Optimization (PSO). Simulations were conducted for the design of quadrature hybrids intended to operate in the 85-115 GHz band using a fully tuned and validated version of the algorithm. We present quadrature hybrids designs which are optimized with respect to operational requirements for the scattering parameters and amplitude imbalance. Furthermore, the resulting designs take into account machining constraints related to cost and feasibility requirements. This method can be easily extended to optimize other microwave devices and waveguides for radio astronomy applications, with the benefit of speeding up the design process as well as reducing the computational costs.**

Keywords—quadrature hybrid, directional coupler, optimization algorithm, amplitude imbalance, millimeter and submillimeter device.

I. Introduction

Radio astronomy has highly demanding standards for microwave devices, often requiring ultra-wide band operability, high sensitivity, and noise rejection. For this reason, research into the design of microwave components for band widening within realistic manufacturing constraints is an ongoing effort [1][2]. In this paper we introduce a novel geometry optimization based on an evolutionary algorithm, that has been applied to quadrature hybrids operating in ALMA (Atacama Large Millimeter/submillimeter Array) Band 3 (85-115 GHz). Our reported results are part of an ongoing research project focusing on the design of a quadrature hybrid covering the ultra-wide ALMA Band 2+3 (67-115 GHz). Our approach to the problem of quadrature hybrid optimization is based on the exploration of the geometric parameter space of standard multi-branch couplers using the Particle Swarm algorithm.

II. Classical Quadrature Hybrids

Multi-branch couplers are widely used in heterodyne receivers. Special attention has been paid to standard designs consisting of two main waveguides connected by branches without further modifications to the guides [4]. Even though an eight-branch model has been proven to comply with the requirements for ALMA Band 3 [3], it has been proposed to increase the number of branches or to use overmoded waveguides to extend the operational band [2]. Further significant modifications have been introduced to the hybrid geometry by drilling extra cavities to the main guides, to add ripples to the signal and consequently reducing the amplitude imbalance at the center of the band [5]-[7]. We applied our method to 8-, 12- and 14-branch geometries, while also including extrusions in the main waveguide to assess their impact on the amplitude imbalance.

III. Quadrature Hybrid Optimization

Our optimization method is based on the Particle Swarm (PSO) evolutionary algorithm together with the Surrogate-Based Optimization (SBO) heuristic method. The algorithm seeks to find the waveguide and branches dimensions stored in a vector called a *particle,* that minimizes a fitness function (FF), while complying with any electromagnetic constraints. In this work we have used those set by ALMA, namely: a) scattering parameters S_{31} and S_{21} are expected to be close to -3 $\pm$0.5 dB, which also ensures keeping the amplitude imbalance below 1 dB [5], and b) the S_{11} and S_{41} parameters must stay below -15 dB. To allow the use of standard drilling tools, we set an additional constraint, defined as the ratio between the height of the main waveguide and the width of the branches, with a maximum value of 7.

As for hyperparameter and FF weights tuning, we settled on a scheme that we benchmarked against a well-defined and characterized quadrature hybrid designed for ALMA Band 5 (163–211 GHz) [9]. After we ran several optimization batches with this geometry as a starting point to fine-tune the algorithm and validate our resulting hybrids, we obtained an optimized geometry that improves the result obtained in [9] (see Fig. 1(a)).

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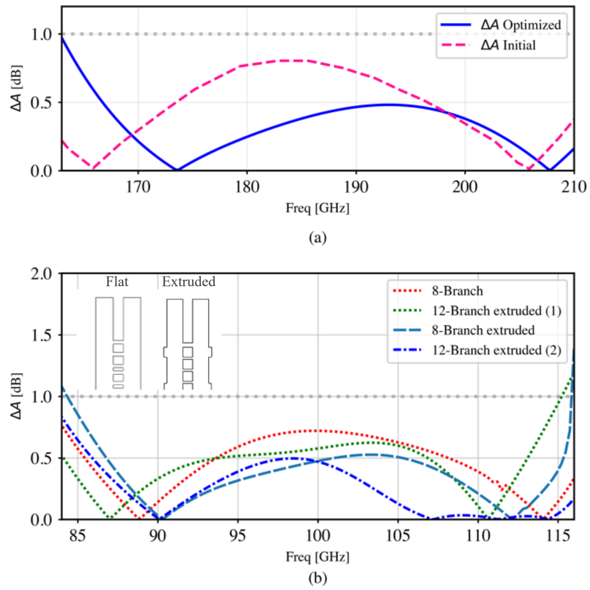

Fig. 1. Optimized quadrature hybrid designs (a) for ALMA Band 5 and (b) ALMA Band 3.

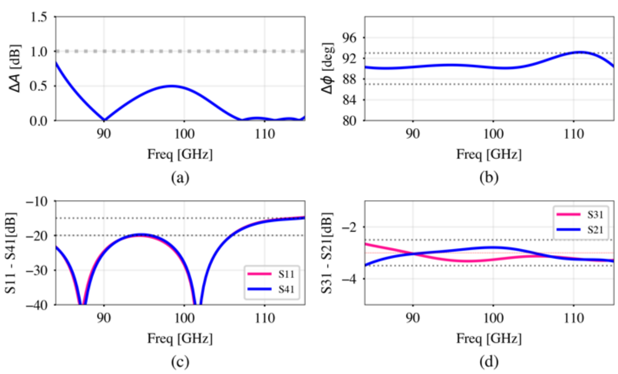

Fig. 2. Resulting (a) Amplitude imabalance, (b) phase imbalance and S-parameters (c,d) for a 12-branch quadrature hybrid incluiding extrusions optimized for ALMA Band 3.

IV. Results in ALMA Band 3

The resulting quadrature hybrid designs obtained for ALMA Band 3 using our optimization method show an excellent simulated performance vis-à-vis the S-parameter and amplitude imbalance requirements. Moreover, resulting geometries are found to be comparable or to improve upon prior results for ALMA Band 3 by fully covering the band with an amplitude imbalance below 1 dB. Fig. 1(b) shows the results for different standard geometries with amplitude imbalance under the expected value, with some hybrids staying below 0.5 dB. The 12-branch hybrid also shows a good S_{11}-S_{41} behavior (Fig. 2) thus an excellent amplitude imbalance contributing to an appropriate IRR [8], all that making it subject of interest for the further analysis and possible fabrication. We performed an additional optimization batch based on our 14-branch hybrid result aimed at widening the current band by an additional 10 GHz, yielding a band spanning from 80 GHz to 116 GHz with full compliance to the established constraints.

V. Conclusions

This novel optimization method provides validated and consistent results for quadrature hybrid designs that comply with electromagnetic constraints that would allow it to operate and improve upon current ALMA Band 3 designs. This method speeds up the design process and it can be extended to the development of other microwave devices for radio telescopes such as feedhorns, orthomode transducers (OMT) and even microstrips. We also found that standard geometries do not provide a viable solution to find a quadrature hybrid to fully cover the entire ALMA band 2+3, as we were only able to reach a solution compatible with (but not wider than) Band W under realistic manufacturing constraints. To achieve the whole coverage, attention must be paid to alternative and novel geometries that can be optimized using the tool herein proposed; this is part of our ongoing work.

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