

学校编码: 10384  
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廈門大學

碩 士 学 位 论 文

# 基于凸优化的波束形成及阵列稀疏化研究

Research on Beamforming and Sparse Array Based on  
Convex Optimization

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论文提交日期: 2016 年 月  
论文答辩时间: 2016 年 月  
学位授予日期: 2016 年 月

答辩委员会主席: \_\_\_\_\_

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## 摘 要

基于阵列天线在无线电系统中各种应用，使阵列综合的研究十分重要。本文根据实际应用系统中的各种需求，结合凸优化的高效、快速以及局部最优解也是全局最优解的优点，研究了各种阵列综合问题及基于凸优化思想的解决方案。

首先，本文基于凸优化算法对理想点源以及考虑阵列天线辐射方向图的阵列的综合方法进行了全面的概述，包含了阵列的无目标优化、最小副瓣优化、最大方向性优化、最大效率优化以及最小阵元数目的优化。并且，针对每个优化目标给出了相应的仿真例子，用以验证相应的综合方法的有效性。

其次，本文提出了矢量场的阵列综合方法。根据给定的期望极化方向，定义了扫描波束的期望主极化和交叉极化方向，并进一步给出了主极化方向性系数的定义，它可以更为准确的表征天线集中辐射主极化分量的程度。在没有副瓣约束和交叉极化约束的条件下，给出了任意阵列主极化方向性系数最优解的解析表达式。并且，在含副瓣约束、零陷约束以及交叉极化约束的条件下，我们发展了一种基于凸优化的高效数值综合方法，实现多约束条件下的主极化方向性系数的优化。数值阵列综合结果表明了本文所提出的最优主极化方向性系数解析解的正确性，以及这种可以综合考虑副瓣约束、零陷约束和交叉极化约束的数值方向性优化方法的有效性。

然后，本文提出了一种可以实现最小间距可控的扫描稀疏阵列的综合方法。此方法主要分为两步，第一步是一个迭代的反复加权 $l_1$ 范数的优化，用以实现没有间距要求的波束扫描稀疏阵列；第二步是通过一系列的阵元合并和阵元的激励及位置的不断微扰用以满足最小间距可控的条件。基于本文提出的这一方法，我们给出了一个扫描范围从 45 度到 135 度的最小间距要求为 0.5 个波长的稀疏阵列的设计仿真。

最后，本文针对实际中的会出现的误差，基于阵列综合后的结果进行理论上的误差分析，并且通过仿真与理想情况下的阵列进行副瓣电平、方向性系数、交叉极化电平的比较，使得对阵列综合的问题分析及解决更加全面。

**关键词：**凸优化；矢量综合；最小间距可控扫描稀疏阵列；误差分析

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## ABSTRACT

Based on the application of array antenna on radio systems, research on array synthesis is very important. According to the requirements of application system in practical, combing convex optimization with advantages of efficient, fast, and local optimal solution equal to global solution, a variety of array synthesis problems and their solutions based on convex optimization are studied in this paper.

First of all, we give a comprehensive overview of array synthesis algorithm of ideal point source and antenna taking scalar radiation pattern into account based on convex optimization, including optimization with none goals, optimization of minimum sidelobe, optimization of maximum directivity, optimization of maximum efficiency, and optimization of the minimum number of array elements. What's more, the corresponding simulation examples are given for each goal to verify the optimization synthesis method.

Secondly, we propose the method of array synthesis in vector fields. Definitions of the desired co-polarization and cross-polarization directions are given for a scanned beam pattern according to a desired polarization direction. Furthermore, the co-polarization directivity is defined to more accurately represent the degree of the concentration of co-polarization field over the total radiated power. With this definition, the co-polarization directivity can be optimized. Its analytical expression can be derived when no any pattern constraints exist. In more general cases in which the constraints on the sidelobe level, nulling points and cross-polarization level exist, an efficient numerical algorithm based on convex optimization is proposed. Some numerical synthesis experiments are conducted, and the results show the effectiveness and robustness of the proposed synthesis techniques.

Next, we propose a new method to design a beam-scanning sparse array with minimum spacing constraint. The proposed method consists of two optimization steps. In the first step, an iterative reweighted  $l_1$ -norm optimization is used to obtain an

initial sparse array without minimum spacing constraint. In the second step, we carry on a series of element combination and perturbations to meet the minimum spacing constraint. An example is given to design a sparse array which has the minimum spacing of 0.5 wavelength and the beam scanning from  $45^\circ$  to  $135^\circ$ .

Finally, as in practical applications, there may exist errors in antenna manufacturing, we carry on error analysis in theory in array synthesis. And we contrast the pattern parameters including sidelobe level, directivity, cross-polarization level, between array with errors and ideal array. Consequently the analysis in array synthesis problems and solution on these problems will be more comprehensive.

**Key Words:** convex optimization; vectorized pattern synthesis; beam-scanning sparse array with minimum spacing constraint; error analysis

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