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新型高功率微波共轴模式转换器及模式转换天线研究

袁成卫　著

国防科技大学出版社

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序　言

积淀孕育创新，智慧创造价值。

寒窗苦读，拼搏奋斗的积淀凝聚成一本本厚积薄发的论文。博士学位论文是博士生学术水平、科研能力、创造性成果的集中体现，也是学校研究生教育水平、学术水平和创新能力的重要标志。全国博士学位论文水平反映了我国高层次创新型人才培养的质量。作为国家21世纪教育振兴行动计划的重要内容，教育部每年评选100篇左右的全国优秀博士学位论文。该举措已成为提高研究生培养质量、鼓励创新、促进高层次创造性人才脱颖而出的重要措施。

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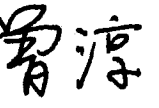
文。

睿智颖悟，优秀博士学位论文展现给我们的不仅仅是丰硕的科研成果，更是巨大的精神财富。全国优秀博士学位论文是我国优秀博士学位论文中的杰出代表，全国优秀博士学位论文作者是具有创造能力和竞争能力的高层次创造性人才，是支撑国家崛起的骨干创新力量。认真总结全国优秀博士学位论文的成功经验，对于进一步提高博士生教育的整体水平，培养数量更多、水平更高的高层次创造性人才，具有十分重要的启示作用。2005年3月，我们汇集出版了我校2004年及之前获得的10篇全国优秀博士学位论文和全国优秀博士学位论文提名论文；2007年4月，我们又汇集出版了我校2005—2006年获得的4篇全国优秀博士学位论文和全国优秀博士学位论文提名论文。在此基础上，现将我校2007—2008年获得的6篇全国优秀博士学位论文和全国优秀博士学位论文提名论文汇集出版。此举旨在为广大在学博士生及其导师树立高水平博士学位论文的范本和学习榜样，也期望进一步推动我校研究生教育改革的深入发展，以培养高层次创新性人才为目标，认真总结创新性人才的培养经验和方法，深入探讨博士生教育改革的思路和措施。

当今世界，科学技术日新月异，科技创新已经成为社会生产力解放和发展的重要标志。科学技术的迅猛发展正在引发一场广泛而深刻的军事变革，信息化战争时代已经来临。在新的历史条件下，面对世界新军事变革的严峻挑战，面对推进中国特色军事变革和军事斗争准备的紧迫需求，军队研究生教育的地位和作用比以往任何时候都更加突出。

国防科技大学承担着为国家安全和军队信息化建设、研究开发国防高科技和先进武器装备、培养军队高级工程技术和指挥人才的历史使命，是

我军实现新军事变革和军队信息化建设的高层次人才培养和科学研究重要基地。提高人才培养的质量已成为我们现阶段亟须关注的问题之一。我们要在培养大批各类专业和指挥人才的同时，努力为优秀创新人才的脱颖而出创造条件。尤其要下功夫造就一批真正能站在世界科学技术前沿的学术带头人和尖子人才，以应对世界新军事变革的严峻挑战，为推进中国特色军事变革做出新的更大贡献。

国防科学技术大学研究生院 

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新型高功率微波共轴模式转换器及模式转换天线研究

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国防科学技术大学研究生院
二〇〇六年三月

Investigations of Novel Coaxial Mode Converters and Mode-Transducing Antennas for High-Power Microwave

Candidate: **Yuan Cheng-wei**
Supervisor: **Prof. Zhong Hui-huang**
Prof. Liu Qing-xiang

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摘　要

目前，多数高功率微波源，如虚阴极振荡器、相对论返波管、磁绝缘线振荡器等，产生的微波模式都为旋转轴对称模，如圆波导 TM_{01} 和同轴 TEM 模等。这些模式若直接发射或用于驱动一些传统天线，将产生轴向为零的环状远场方向图，其能量分散、增益低，不利于高功率微波的定向发射与传输。为此，通常要应用高功率微波模式转换器将 TM_{01} 或同轴 TEM 模转变为易于定向发射的圆波导 TE_{11} 模，再向外发射，或者采用特殊结构的模式转换天线直接辐射。然而，到目前为止，几种高功率微波模式转换器或模式转换天线，如双弯曲型模式转换器、Vlasov 天线(转换器)和 COBRA 天线等，尚不能很好地解决天线的共轴发射或紧凑化设计等问题。在此背景下，我们提出了一种新型共轴模式转换器——同轴插板式模式转换器，它通过在同轴波导内插入几块金属板实现微波模式转换，具有转换效率高、输出与系统共轴、结构紧凑以及实现容易等优点。论文对该模式转换器进行了详细的理论分析、数值仿真和实验研究，并在此基础上提出了更为紧凑的、集模式转换和定向发射于一体的模式转换天线。另外，为了实现模式转换器输出圆波导 TE_{11} 模的定向辐射，论文还研究了一种紧凑型的介质透镜喇叭天线。最后，论文还对适用于高频微波的共轴模式转换器进行了初步探索，设计了输入输出共轴的三弯曲型模式转换器，并提出了一种易于实现的多节直波导模式转换器。论文的研究内容主要包括以下几个方面：

(1)提出并系统地研究了同轴插板式模式转换器

首次提出了通过改变同轴波导内不同区域相位实现模式转换的思想，设计了同轴插板式模式转换器的原理型结构。对同轴插板式 TEM - TE_{11} 模式转换器进行了系统的分析，包括模式转换器内发生的各个模式转换过程、模式转换器的反射特性以及频率特性等，获得了许多有益的结论。设计了同轴插板式 TM_{01} - TE_{11} 模式转换器，并对其进行了详细的数值仿真和实验研究。该模式转换器在中心频率上的转换效率大于 99%，转换效率大于 90% 的频带宽度超过 15%。实验结果与理论分析基本一致。在工程设计上和实际应用中，实现了该模式转换器和高功率微波源虚阴极振荡器的一体化设计，在

实验中获得了输出为 TE_{11} 模的高功率微波，微波功率大于 1GW。

(2)为了实现圆波导 TE_{11} 模的定向发射，研究和设计了紧凑型介质透镜喇叭天线

通过分析比较得出，利用口径上加载介质透镜的圆锥喇叭可以设计出辐射圆波导 TE_{11} 模的紧凑型高功率微波天线。用射线法建立了介质透镜喇叭天线辐射场的计算方法，并对几种不同形式的介质透镜进行了计算、分析和比较。结果表明，平凸型介质透镜喇叭天线可以在较小的轴向尺寸下获得较高的增益，其反射也最小。所设计的平凸型介质透镜喇叭天线在 2.5 ~ 7.0GHz 的频率范围内口径效率大于 75%，反射小于 -17dB。在 4.0GHz 时，该天线的长度和口径面积仅分别相当于同增益圆锥喇叭的 47% 和 63%。该喇叭天线和前述 TM_{01} - TE_{11} 模式转换器组成了一套紧凑型高功率辐射微波发射系统，并已应用到高功率微波装置之中，在所进行的一系列高功率微波实验研究中，获得了理想的结果，体现了良好的性能。

(3)引入了一种紧凑的同轴喇叭结构，并由此提出了一种新型模式转换天线

为了进一步缩小发射系统的体积、减轻其重量，引入了一种可以辐射同轴 TE_{11} 模的紧凑型同轴圆锥喇叭，该喇叭可以和缩短了的同轴插板式模式转换器有机结合，设计出结构紧凑的模式转换天线。此处，模式转换器能够缩短是由于它输出同轴 TE_{11} 模，而不需将同轴 TE_{11} 模进一步转变为圆波导 TE_{11} 模。对同轴喇叭进行了系统的研究，结果表明，该喇叭具有纵向尺寸短、口径效率高、频带宽和副瓣小等优点。设计了中心频率为 1.76GHz 的模式转换天线，该天线的理论增益为 17.6dBi，口径效率大于 77%，天线的冷测结果与数值计算结果一致性良好。同时还将该天线应用到高功率微波系统中，进行了与高功率微波源 MILO 的联合实验，获得了轴向辐射的高功率微波笔形射束，微波功率大于 3GW。同时，为了满足在更多情况下的应用需求，论文还进行了高频、大尺寸情况下模式转换天线的设计，进一步扩展了同轴插板式模式转换器的应用范围。

(4)提出了圆极化模式转换器并进一步设计了圆极化模式转换天线

通过增加插板数量、改变插板之间的长度关系，首次提出和设计了把同轴 TEM 模转变为圆极化同轴 TE_{11} 模的高功率微波圆极化模式转换器，并对其进行了详细的分析。继而，将其与同轴圆锥喇叭结合，设计了圆极化模式转换天线。优化设计了中心频率为 4.0 GHz 的两种形式的圆极化模式转换天线，第一种天线具有结构简单、易于设计的特点，而第二种天线则结构相对紧凑、口径效率高。其中，第一种天线在长度 38.5cm、口径 32.0cm 的尺寸下获得了增益为 19.3dBi、口径效率为 47.4% 的理论计算结果；而优化

设计的紧凑型天线则在长度 33.0cm、口径 30.8cm 的结构尺寸下获得了增益为 19.8dBi、口径效率为 57.7%的理论结果。对紧凑型的第二种天线进行了实验测量，测量结果与计算结果基本一致。此外，还设计了将同轴 TEM 模转变为圆波导 TE_{11} 模的高效率圆极化模式转换器，在中心频率 4.05GHz 上，该转换器的转换效率为 99%，轴比为 1.01；在 3.80～4.35GHz 的频率范围内，其转换效率大于 90%（带宽约为 13.6%），轴比小于 1.40。

(5)对高频共轴模式转换器进行了初步探索

尽管同轴插板式模式转换器具有许多优点，但在高频微波波段（如 X 波段），其使用仍然受限，主要体现在在高频情况下，其尺寸小、结构相对复杂、功率容量较低。相反，弯曲形模式转换器具有结构简单、功率容量高等优点，适合于高频微波系统。为了设计适用于高频系统的共轴模式转换器，论文发展了传统的双弯曲型模式转换器，通过采用相位重匹配技术，设计了一种输入输出共轴的三弯曲型 TM_{01} – TE_{11} 模式转换器。该转换器由三段常曲率弯曲圆波导和两段直圆波导组成。所设计的 7.0 GHz 模式转换器在中心频率上的转换效率大于 99%，在 6.5～7.5GHz 的频率范围内转换效率大于 90%，对应模式转换器的带宽（$\eta \geq 90\%$）为 14.3%. 进一步地，为了解决弯曲形模式转换器由于加工困难而带来的应用问题，提出了一种易于加工的多节直波导模式转换器，它仅由几节直圆波导倾斜连接构成，其外形可以是输入输出共轴的 Ω 形，也可以是非共轴的 S 形，可以应用于多种场合。初步设计了五节式 Ω 形模式转换器和五节式 S 形模式转换器，两者在中心频率上的转换效率均达到了 98.8%，Ω 形模式转换器的相对带宽为 12%，S 形模式转换器的相对带宽达到 19%。

关键词： 高功率微波；模式转换器；模式转换天线；天线；透镜喇叭天线；轴对称模式

ABSTRACT

Many high-power microwave (HPM) sources, such as Virtual Cathode Oscillators (Vircators), Relativistic Backward Wave Oscillators (RBWOs), and Magnetically Insulated Transmission-line Oscillators (MILOs), generate azimuthally symmetric output modes, including the TM_{01} circular waveguide mode and the TEM coaxial waveguide mode. If radiated directly or used to drive conventional antennas, these modes will produce a kind of doughnut-shaped radiation pattern, with a boresight null. Usually, mode converters, such as the dual bent TM_{01} – TE_{11} mode converter and the Vlasov radiator, are considered to transform the TM_{01} mode into TE_{11} mode. Unfortunately, their input and output ports are not aligned on the same axis, which affects the compactness of the whole HPM system. Mode-transducing antennas, such as the COBRAs, have also been explored, but they are still not suitable for designing compact HPM radiation systems, since their aperture efficiencies are typically low. In this dissertation, a novel kind of mode converter that transforms the coaxial TEM (or circular TM_{01}) mode into the TE_{11} circular waveguide mode, called as coaxial plate-inserted mode converter (CoPIMC), is proposed. It has the virtues of high conversion efficiency, co-axis with system, compactness, and easy fabrication. The mode converter is studied systematically with theoretical analyses, numerical simulations, and experimental tests. Furthermore, mode-transducing antennas, composed of shortened CoPIMCs and a compact coaxial horns, are also proposed and investigated. Additionally, in order to radiate the TE_{11} circular waveguide mode from the mode converter, a compact dielectric lens-horn antenna is also studied. At last, novel coaxial mode converters for high frequency applications are explored, and a tri-bend serpentine mode converter and a kind of multi-straight-waveguide mode converter are proposed and designed. The detailed contents and the innovative work include the followings:

(1) A novel mode converter is proposed and studied systematically

In this dissertation, a novel concept to realize a TEM – TE_{11} mode conversion with inserting several metal plates into a coaxial waveguide is proposed, and the prototype of a TEM – TE_{11} mode converter is designed. This converter is analyzed systematically, including the mode

conversion processes, the reflection characteristics, and the frequency features. Many valuable conclusions are achieved. Moreover, a $TM_{01} - TE_{11}$ mode converter with the central frequency of 3.6 GHz is designed and simulated. It has a high convession efficiency of over 99% at 3.6 GHz, and its bandwidth exceeds 15% with the conversion efficiency greater than 90%. The measured results are in good agreement with the simulated ones. In engineering design and HPM application, the converter is integrated with a HPM source. It is also tested in the vircator HPM source. The whole device (including the vircator and the mode converter) works well and outputs a TE_{11} circular waveguide mode with a peak power of over 1GW.

(2) In order to radiate the TE_{11} circular waveguide mode directionally, a compact dielectric lens-horn antenna is developed

It is shown that a short conical horn with a dielectric lens loaded in the aperture is suitable for designing a compact HPM antenna for the TE_{11} circular waveguide mode. The ray tracing method is employed in calculating the radiation patterns of the lens-horns. Three types of dielectric lens, in concrete, hyperbolical lens, elliptical lens, and plano-convex lens, are studied and compared. The results show that a conical horn with a plano-convex lens can produce higher gain and lower reflection than other two types of lens-horn with the same dimension. Therefore, a plano-convex lens-horn is designed, simulated, and tested. Over a wideband frequency range of 2.5 to 7.0 GHz, its aperture efficiency is greater than 75% and its reflection is less than-17dB. At 4.0 GHz, the length and the aperture area of the antenna is only about 47% and 63%, respectively, of a conventional conical horn that has the same gain. The designed lens-horn, together with the above-mentioned $TM_{01} - TE_{11}$ converter forming a compact HPM radiation system, has been applied in a HPM system and was experimentally studied in our laboratory. In the HPM experiments, it represents a good performance.

(3) A new kind of mode-transducing antenna is presented and investigated systematically

In order to get a more compact radiation system, a coaxial conical horn is introduced to work together with a shortened CoPIMC. In such a case, the converter is shortened for it outputs coaxial TE_{11} mode (compared with that of outputting circular TE_{11} mode). Here, the shortened converter and the coaxial conical horn are interdependent, so they are regarded together as a mode-transducing antenna. The coaxial horn is studied with finite-element methods (FEM). The results indicate that this type of horn is characterized by high aperture efficiency, short axial length, wide bandwidth, and low sidelobes. Moreover, a mode-transducing antenna at 1.76 GHz is designed with a gain of 17.6dBi and an aperture efficiency of 77%. The measured results

agree with the simulated ones. The HPM experiments of the antenna, which has been applied in a HPM equipment, were also performed with an L-band MILO, outputting pencil beam in boresight with peak-power over 3 GW. In addition, an improved mode-transducing antenna suited for high frequencies and oversized waveguides is developed.

(4) Novel circularly polarized coaxial plate-inserted mode converters (CP-CoPIMCs) and circularly polarized mode-transducing antennas are investigated

In this part, a novel CP-CoPIMC that converts coaxial TEM mode to CP coaxial TE_{11} mode is proposed by inserting more metal plates into a coaxial waveguide, and it is investigated in detail. Furthermore, the CP-CoPIMC is combined with the coaxial conical horn, constructing a CP mode-transducing antenna. Two kinds of CP mode-transducing antennas centered at 4.0 GHz are developed, one is slightly larger but easy to design, and the other is more compact. The sizes of the first one are of 38.5 cm in length and 32.0 cm in aperture diameter with a gain of 19.3 dBi and an aperture efficiency of 47.4%. Whereas, the corresponding dimensions of the compact one are 33.0 cm and 30.8 cm, respectively, with a gain of 19.8 dBi and an aperture efficiency of 57.7%. The compacter second one was also tested in lower power and high power cases, respectively. The measurements are in agreement with the simulations. Moreover, a CP-CoPIMC that converts the coaxial TEM mode to the CP circular TE_{11} mode with high conversion efficiency is also presented. The calculated results show that it has a high conversion efficiency of 99% at 4.05GHz with an axial ratio of 1.01. Over the frequency range of 3.80 to 4.35 GHz, the conversion efficiency exceeds 90% with a bandwidth of about 13.6% and an axial ratio of less than 1.40.

(5) New kinds of coaxial mode converters for high frequency systems are explored

Though the CoPIMCs have many good features, they are complex in structure and not satisfactory for some applications, especially at high frequencies, such as in X band, for their power-handing capacities are not enough in high frequency regions. On the contrary, serpentine mode converters are very suitable for high frequency circumstance, because of its simplicity and high power-handing capacity. In order to explore some novel coaxial mode converters for high frequency applications, a tri-bend serpentine TM_{01} – TE_{11} mode converter with input and output ports aligned on the same axis is developed by using phase-rematching technique. The converter is formed with three constant-curvature bent waveguides and two straight waveguides. A mode converter of this kind centered at 7.0 GHz is designed. The efficiency of the conversion from TM_{01} to TE_{11} exceeds 99% at 7.0 GHz and 90% over the frequency range of 6.5 to 7.5 GHz (the corresponding relative bandwidth for $\eta \geq 90\%$ is 14.3%). Moreover, to reduce the

difficulty of fabricating a serpentine mode converter, which has bent circular waveguides, a new kind of mode converter that is very easy to fabricate, which we call as multi-straight-waveguide mode converter, is proposed. This kind of mode converter is composed of only several straight circular waveguides connected with each other at certain angles, and it has a profile of Ω-shape or S-shape. A five-sector Ω-shape mode converter and a five-sector S-shape mode converter are designed, respectively. They both have a conversion efficiency of 98.8% at center frequency. The Ω-shape one has a relative bandwidth of 12%, and the S-shape one has a relative bandwidth of 19%.

Key words: High-power microwave (HPM); mode converters; mode-transducing antennas; antennas; dielectric lens-horn; azimuthally symmetric mode

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