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学 位 記 番 号	総研大甲第 1667 号
学位授与の日付	平成26年3月20日
学位授与の要件	物理科学研究科　宇宙科学専攻 学位規則第6条第1項該当
学 位 論 文 題 目	GaN HEMT を用いた宇宙環境耐性に優れる小型軽量高効率な次世代宇宙用電力増幅回路に関する研究
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論文内容の要旨

Summary of thesis contents

Research on a space-tolerant, small-sized, lightweight and highly-efficient next generation power amplifier using a GaN HEMT

One of the most indispensable impacts on onboard power consumption has been generally caused by a transmitting power amplifier among the other spacecraft bus subsystems. Due to the large amount of power consumption, it is inevitable that the size (or footprint) and weight of the transmitting power amplifiers become large for heat release. Therefore, developing a highly-efficient onboard transmitting power amplifier is one of the great issues for future various space missions. From these backgrounds, this research concerns the world's first space-use amplifier circuit using a gallium nitride (GaN) high-electron mobility transistor (HEMT) for the realization of space-tolerant, small-sized, lightweight, and highly-efficient onboard transmitting power amplifier.

Regarding onboard transmitting power amplifiers, travelling-wave tube amplifier (TWTA) and solid-state power amplifier (SSPA) have been mainly used. In general, TWTA uses a vacuum tube called traveling-wave tube and its component total efficiency is up to 35 to 55%. In contrast, SSPA usually uses a gallium arsenide (GaAs) based field-effect transistor (FET) and its total efficiency is around 20 to 30%. Due to the highly-efficient characteristics, TWTA has been mainly used as a high power amplifier dealing with more than 20-W output power. However, with respect to mechanical environment tolerance, lifetime, occupied area (footprint), and discharge risk, SSPA is superior to TWTA because TWTA uses a fragile sculpted-glass tube and needs high voltage (kV) operation. Thus, highly-efficient SSPA has been strongly required and a highly-efficient amplifier circuit is quite important to achieve this. In this research, GaN is selected as an amplification device among the other semiconductor devices since it has the characteristics of high breakdown voltage and high thermal conductivity in addition to wide band gap. As a result, in comparing Johnson's figure of merit, the suitability as high power and high frequency device, GaN is up to about 100 times higher than GaAs. In addition, GaN is expected to handle large RF power in small size with high efficiency compared to GaAs since GaN's current density in HEMT structure is larger than that of GaAs as well as breakdown voltage and thermal conductivity of GaN is superior to those of GaAs. Here, researches concern amplifier using GaN have been reported a lot. However, they mainly focus on the realization of high power, high frequency and high efficiency. In other words, how to apply GaN to amplifier circuits for space applications has never proposed. Therefore, this research focuses on the following to achieve this:

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I: Device selection method of X-band GaN HEMT for space-use amplifier.
II: X-band, highly-efficient, highly-reliable and highly-accurate amplifier design/evaluation method that can minimize the error between design and measurement in order to enhance the reliability for space applications as well as achieve high efficiency.
III: Mounting method of GaN HEMT considering harsh space environment.

With respect to the device selection of X-band GaN HEMT for space-use amplifier, it requires completely different attitude from the selection of S-band, terrestrial GaN HEMT. This is because that there are so many highly-efficient, internally-matched and packaged GaN HEMTs in S-band, but no such devices in X-band. In addition, realizing high power in parallel structure using low power devices and operating with active thermal control system can be done only for terrestrial applications since there are no strict restrictions regarding size, weight and heat release environment. Considering these things, this research selects externally-matched and bare-chip GaN HEMT that can deal with high power in single-end structure. Moreover, GaN on silicon carbide (SiC) HEMT is selected so as to enhance the space applicability since SiC has good material properties such as high thermal conductivity and wide band gap compared to silicon (Si). To evaluate the validity of the device selection method, X-band GaN on SiC HEMT and S-band GaN on Si HEMT are tested by thermal vacuum and radiation (total ionizing dose). There are no specific differences between X-band GaN on SiC HEMT and S-band GaN on Si HEMT in thermal vacuum test whose temperature range is from -20 to 60 degC. However, in total ionizing dose test using 60Co, S-band GaN on Si HEMT is degraded up to 1.37 dB of output power and 21.7% of PAE after 320-krad exposure even though X-band GaN on SiC HEMT is not affected at all. Therefore, it is confirmed that proposed device selection method of X-band GaN HEMT is feasible for space-use amplifier.
Next, the realization of X-band, highly-efficient, highly-reliable and highly-accurate amplifier design and evaluation method is one of the great issues for space applications. At the beginning, we conduct both small signal and large signal design using the nonlinear device model that is constructed based on Angelov GaAs FET nonlinear model and the model parameters are modified for GaN HEMT on the basis of measurement RF and DC characteristics. In this case, although fabricated amplifier demonstrates superior (highly-efficient) performance such as 10.1 dB of small signal gain, 42.6 dBm of maximum output power and 47.3% of maximum PAE at 8.4 GHz, the errors between design and measurement are not enough small to enhance the reliability for space applications. For instance, the error of small signal gain is 2.2 dB, peak frequency is 129 MHz, the maximum power at 8.4 GHz is 0.3 dB and the maximum PAE at 8.4 GHz is 4.4%. To reduce these errors, we propose to estimate the error of bonding wire between model and measurement by modifying the length of

bonding wire in measurement since the model behavior of bonding wire in circuit simulator is uncertain although it has a profound effect on the peak frequency in measurement. Here, in general, the errors due to the uncertainties of bonding wire are tried to reduce by adjusting the fabricated circuit patterns, such as adding or cutting the copper substrate by trial and error since modifying the length of bonding wire in measurement is quite difficult. However, this kind of method leads to a considerable change in the fabricated circuit patterns. As a result, it becomes extremely-difficult to evaluate the differences between design and measurement fairly as well as to achieve highly-reliable and highly-accurate design and evaluation. By contrast, since proposed estimation can remove the uncertainties of bonding wire without any adjustment of the fabricated circuit patterns, we can fairly estimate the differences between design and measurement. Therefore, it is possible that the remaining errors due to the uncertainties such as parasitic capacitance or parasitic inductance caused by mounting are estimated by adjusting parameters with respect to drain, gate and source capacitances and inductances in the nonlinear model. Consequently, the error of small signal gain becomes 0.5 dB, peak frequency becomes 18 MHz, the maximum power at 8.4 GHz becomes 0.2 dB and the maximum PAE at 8.4 GHz becomes 1.2%. As observed above, we achieve X-band, highly-efficient, highly-reliable and highly-accurate amplifier design and evaluation method for space applications by constructing a nonlinear model in order to conduct a certain level of highly-accurate design and make it possible to adjust the model parameters, estimating the uncertainties in measurement without any adjustment of the fabricated circuit patterns and adjusting the parameters in the constructed nonlinear model.

Finally, a mounting method considering harsh space environment is quite important since high-power and continuous-wave (CW) operation without any active thermal control is required in space applications as well as heat release characteristics is demanded to be free of the influence of space environment such as vibration, shock acceleration and vacuum. To achieve this, this research proposes that GaN on SiC HEMT is directly mounted on a convex–structure copper case with high thermal-conductivity solder paste (Sn-3.0Ag-0.5Cu). In comparing with the existing mounting method such as through-hole structure or subcarrier structure by thermal analysis, it is confirmed that proposed mounting method has the best thermal release characteristics of all. In addition to the analytical approach, proposed mounting method is evaluated in high temperature, thermal vacuum, vibration and shock acceleration tests. In the high temperature test using Peltier device in the atmosphere, when the temperature of a base plate is 73.3 degC, that of the fabricated amplifier is 85.5 degC, as a result, the temperature difference in the atmosphere is 12.2 degC. After reaching the equilibrium temperature, output power difference during 1-hour continuous operation stays no more than 0.1 dB. In addition to the temperature test, it is confirmed that heat release characteristics is not affected by vacuum condition since the temperature difference between the base plate and the fabricated amplifier results in 12.0 degC under both low temperature (-20 degC) and high temperature (+60 degC) vacuum conditions in a thermal vacuum test. Moreover, output difference is also less than 0.1 dB after vibration and shock acceleration tests. Therefore, it can be said that the validity of proposed mounting method for space application is confirmed.

The output power and efficiency achieved in this research, such as the maximum output power of 42.6 dBm and the maximum PAE of 47.3% at 8.4 GHz, are comparable to other related GaN amplifier researches. In addition, for the world's first actual use in space of SSPA using GaN HEMT in PROCYON project, SSPA engineering model (EM) using the GaN HEMT amplifier circuit achieved in this research is developed. Developed SSPA EM achieves more than 15 W of output power with 33.8% of total efficiency. This efficiency is the highest of all the existing X-band onboard SSPAs. To be more precise, it is about 8.0 to 13.4% higher than that of the other SSPAs. Additionally, radiation-hardiness SSPA is easily achievable due to the excellent material properties of GaN. Thus, the freedom of onboard SSPA's place increases. As a result, it may be possible to set an SSPA just beneath a transmitting antenna where radiation condition is much severer than the other place inside of a spacecraft. Consequently, feeder loss is expected to be mitigated and link margin is supposed to increase. In addition, GaN is also expected to make SSPA small and lightweight because it can deal with large amount of RF power in small size. Therefore, after the world's first actual use in space by PROCYON project, the SSPA is expected to be used in ultra-small deep space explorers launched by Epsilon rockets or large satellite for space science or space exploration missions in the near future. Moreover, it is also expected to apply the SSPA using GaN HEMT to a high power transmitting amplifier for ground stations. From these results, the world's first design, fabrication and evaluation method of a space-use high power amplifier using GaN HEMT for space-tolerant, small-sized, lightweight and highly-efficient SSPA comparable to TWTA is achieved.

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博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

出願者は，電力増幅器を中心とした宇宙機用通信系のデバイス・回路モジュールならびにサブシステムの研究を行っており，本研究では，宇宙機バスシステムの中で最大規模の消費電力を持ち，高速通信や超遠距離通信等の大電力化要求に対して大きな制約となる，電力増幅器を対象とした．本論文では，GaN・高電子移動度トランジスタ（HEMT）による小型軽量高効率化を目的とした宇宙用 X 帯固体化電力増幅器（SSPA）の設計・試作・評価と，宇宙環境耐性の向上に関する研究結果を述べている．具体的には，GaN・HEMT を用いた電力増幅器の非線形モデルを構築し，この非線形モデルを用いた大信号でのシミュレーションを行うことで，実測値との誤差の少ない設計評価手法を確立した．こうした設計評価手法と放熱特性に優れた実装方法を用いることで，GaN・HEMT を用いた電力増幅器の大幅な効率向上を実現し，最大出力 42.6dBm，電力付加効率（PAE）47.3%の安定動作を達成した．また，宇宙環境耐性評価試験を実施し，宇宙用回路モジュールの新しい実装方法によって，強い放射線耐性，高温真空条件下での安定動作を世界で初めて実現している．

本論文では，第 1 章にて背景，目的，および本論文の構成について述べ，第 2 章では高効率宇宙用電力増幅回路の実現に向けて，本研究における設計目標，関連研究と本研究の位置付け，本研究で解決すべき課題とそれに向けたアプローチについて述べている．第 3 章においては本研究の学術的価値の高い GaN HEMT を用いた宇宙用電力増幅回路設計に関して，X 帯搭載用デバイスの選定手法の提案，選定デバイスの実測値に基づく非線形モデルの構築，小信号・大信号を用いた設計等，本研究における宇宙用電力増幅回路の設計手法について述べており，第 4 章では前章の基礎理論に基づいて，GaN HEMT を用いた宇宙用電力増幅回路の作製および評価として，搭載用を考慮した実装方法の詳細，作製した回路の RF 特性評価，動作点による RF 特性の改善，SSPA コンポーネントとしての評価，宇宙用としての高信頼・高確度設計のための不確定要素の推定，非線形モデルのパラメータ調整等について記述している．さらにその成果は，宇宙用電力増幅回路を用いた SSPA の世界初の宇宙実証に向けて，PROCYON プロジェクト搭載用として開発した SSPA のエンジニアリングモデル（EM）の評価を実施し，コンポーネントの総合効率 33.8 %以上が期待できるものとなった．これは，20～26 %程度に留まる現状の X 帯の搭載系 SSPA と比較した際にも大幅な効率の向上が見込める上に，JAXA や NASA の搭載系進行波管を用いた高出力増幅器（TWTA）の一部の総合効率と比較しても，2～3 %程度の差となるため，TWTA との置換も期待できる．第 5 章では宇宙での実用を目指して，放射線試

験，熱真空試験，温度試験を通した GaN HEMT デバイスの宇宙環境耐性について，提案する搭載用デバイス選定手法・搭載用を考慮した実装方法の宇宙適用性の評価等について述べており，熱真空・放射線いずれにおいても基板の差は大きくは見られないことを示した．さらに，動作周波数の影響を評価するために環境試験前後での周波数特性の評価も行い，試験後の特性の劣化量は，周波数に依存せず全周波数領域で一定となることを確認した．このことは，宇宙用マイクロ波 GaN アンプに関する世界初の実証であり，今後の宇宙マイクロ波回路モジュールの開発に貢献するところ大である．最後の第 6 章では，本研究の結論が記されている．

以上のように，本研究では，宇宙環境耐性の向上，小型軽量高効率化を目的とした GaN HEMT を用いた X 帯の次世代固体電力増幅器の世界初の宇宙実証に向けて，宇宙用電力増幅回路の設計試作評価を実施した．本研究によって，これまでの GaN HEMT を用いた電力増幅回路に関する研究では全く考慮されてこなかった宇宙適用性が確立されたと言える．このように，宇宙用に特化し，デバイスの選定・宇宙環境耐性評価，デバイスのモデル化，増幅回路設計，試作評価といった一連の GaN HEMT を用いた宇宙用電力増幅回路の設計手法の提案，検証はこれまで行われていないことから，学術的にも極めて価値が高い．そしてこの研究の成果は，査読付き学術雑誌論文 3 通（電子通信関係 1 通，航空宇宙関係 2 通）にて論文出版されており，また，その成果が評価され，国際会議において Best Paper Award も受賞している．

以上の結果を踏まえ，本論文は，博士論文として充分な学術水準に達していると判定した．