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学位の種類	博士（工学）
学位記番号	博第1197号
学位授与の日付	2021年3月31日
学位授与の条件	学位規則第４条第１項該当　課程博士
学位論文題目	Study on Wideband Planar Feeding Circuits for Multibeam Array Antennas in Millimeter-Wave Band （ミリ波帯マルチビームアレーアンテナ用広帯域平面給電回路に関する研究）
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論文内容の要旨

Recently, with the explosive growth in the demand for wireless connected devices, the frequency spectrum of millimeter-wave band has been considered as an alternative solution for short range communications with high-speed data transfer rates. Multibeam antennas (MBA) in millimeter-wave band have been ubiquitously applied in various applications such as fixed wireless access, 5G mobile communication systems and high angular resolution automotive radars. Due to the small-scale of antennas utilized in high frequencies, feeding circuits for multibeam antennas are also required a compact size, wideband, and high transmission performance to support huge traffic capacities and easy for integration in RF circuit. In the multibeam antenna systems, the feeding circuits include beamforming networks (BFN) and their connections to antenna elements. Current feeding technologies are facing some problems of poor transmission performance in planar transmission lines as well as high cost in waveguide and finline. Therefore, transmission lines, beamforming and transition technologies are three main factors to determine the transmission and bandwidth performances of the feeding circuit for multibeam array antenna. This dissertation explores design techniques for three objectives: low-loss transmission line, low-loss beamforming network for beam steering capabilities, and transitions between the feeding circuit and array elements or IC chip.

A novel low-loss beamforming network of the well-known Butler matrix using finline in double-layer dielectric substrate is presented in this study. The Butler matrix is a planar network with medium insertion loss compared to other beamforming technologies. Conventional circuits are commonly designed using microstrip and waveguide technologies with the challenges of transmission losses and high cost. The proposed finline design aims to provide a balance between transmission performance and production cost. The finline is constructed by inserting a slotline between two dielectric substrate layers and it is bounded within a closed structure composed of a double-layer dielectric substrate and two rows of via-hole arrangement, contributing to low dispersion and low radiation loss of the characteristics. Then, a 4×4 Butler matrix with 4 switchable beams is realized by using the proposed finline. In addition, a waveguide-to-finline transition structure is invented as a power feeding circuit for the Butler matrix from hollow waveguides. Characteristics of the proposed transition and the Butler matrix were analyzed by the finite element method of high frequency structure simulator (HFSS) and demonstrated by experiments at 79 GHz. Implementing low-loss finline helps the proposed Butler matrix provides a wideband characteristic and an acceptable insertion loss of 2.42 dB. The array factor calculated from the measured amplitudes and phases showed that the Butler matrix produced 4 switchable beams with the beam directions of $+14^{\circ}$, -46.5°, $+46.5^{\circ}$, and -14°, respectively. The proposed beamforming network using finline in double-layer dielectric substrate would be attractive for millimeter-wave multibeam array antennas due to its performance and low cost.

A wideband planar waveguide-to-microstrip transition is proposed as a feeding circuit for the microstrip array antenna. In the conventional structure, the transition operates over a single-transmission mode dominance in the transition, followed by a narrow bandwidth of a single resonance frequency. To deal with this problem, in the proposed transition, via-hole positions are adjusted to add inductance to suppress the predominance of the single-transmission mode at the microstrip port of the transition. Grounded coplanar waveguide mode and parallel plate transmission mode are generated by controlling the positions of adjacent holes to the microstrip line, and double-resonant frequency is obtained under the excitation of two transmission modes. Moreover, to simplify the structure, adjacent holes to the microstrip line are maintained, but the remaining holes are replaced by a choke structure that performs the equivalent function to the via-hole arrangement. A double-resonant frequency with a wide bandwidth of 10.6 GHz (13.8%) is obtained in both structures. The proposed waveguide-to-microstrip transition also achieves a low insertion loss of 0.41 dB at the center frequency of 76.5 GHz.

In addition, when the beamforming network is integrated in the RF circuit, a differential signal generated from IC chip is input to the beamforming network through a hollow waveguide. Therefore, a study of the waveguide-to-differential line is conducted in this dissertation. The IC chip is connected to the waveguide in the state of being mounted on the multi-layer dielectric substrate via a bump structure. Two kinds of waveguide-to-differential line transitions where the hollow waveguide and the IC chip are located on the same side and opposite sides of the PCB substrate were proposed. The transitions achieved a broad impedance bandwidth of 27% (250 GHz – 325 GHz) and 13% (252 GHz – 286 GHz) due to their multiple resonance operation. Moreover, via holes are proposed to arrange surrounding the waveguide profile and transmission line to prevent the leakage power generated by higher-order mode in the multi-layer dielectric substrate. The insertion losses of the transitions were about 0.3 dB and 1.1 dB.

This dissertation consists of six chapters. Chapters 1 and 2 described in detail the background of the study and literature review on the basic theories behind the transmission lines, transitions, and beamforming techniques. Chapter 3 presented the Butler matrix beamforming circuit using the low-loss finline in double-layer dielectric substrate. Chapter 4 and chapter 5 then gave a discussion of the bandwidth extension technique for the planar waveguide-to-microstrip transition and the waveguide-to-differential line transition. The performances and contributions of proposed techniques were concluded in chapter 6.

論文審査結果の要旨

ミリ波・テラヘルツ波の技術は、自動運転等の高分解能センシングや、高速大容量をはじめとした5Gbeyond/6Gの次世代移動通信など、今後、幅広く拡大することが期待される技術である。これらの応用では、アナログ信号でのビームフォーミング技術などの高度な高周波技術が必要となる一方で、高い周波数であるために、伝送線路における低損失化技術が要求される。本論文では、今後、ますます利用周波数が高くなり、これまでの平面線路では伝送損失が深刻になったときに、これに代替しうる新規な伝送線路であるフィンライン伝送線路と、これを用いたマルチビーム給電回路、および伝送線路変換技術について開発した成果をまとめている。

まず、フィンラインは導波管内部に形成されたスロット線路であり、一般に、金属導波管内部に、スロット線路を構成したプリント基板を挟み込むことで構成し、導波管接続の測定装置に、ダイオードやトランジスタなどの制御素子を組み込む高周波スイッチや増幅器を作るのに構成される。この導波管を、近年盛んに研究が進められている基板内導波管に置き換えることで、多層基板内にフィンラインを構成する方法を考案し、導波管の低損失性と、スロット線路の広い高周波回路設計自由度を兼ね備えた新方式のフィンライン伝送線路技術を提案している。本論文では、多層基板内に構成された新方式のフィンラインの伝送特性を、電磁界解析と実験で検証しており、フィンラインの、様々な高周波部品への拡張の可能性について、重要な示唆を与えるものである。

次に、フィンラインの様々な高周波部品への展開の可能性を確認する一形態として、上記のセンシングや次世代移動通信への活用が期待されているマルチビームアレーアンテナの実現に必要な給電回路である、4素子アレーからなる4ビームバトラーマトリックス回路を、フィンラインを用いて設計している。この設計にはフィンライン伝送線路のスロット幅の調整による特性インピーダンスの制御や、分岐回路、ベンド（曲げ）回路などの基本素子の設計と、これらを用いたハイブリッド分配器、クロスオーバ回路、位相調整線路が必要であり、これらを個々に設計するとともに、相互作用も考慮に入れた最適設計をしている。電磁界解析と試作機の実験による評価によって、設計通りの特性が得られ、本手法は、今後のミリ波・テラヘルツ波用伝送線路の重要な選択肢の新たな提案を与えるものである。

そして、次世代無線応用での活用が期待される300GHz帯において、高周波デバイスの入出力線路で多く用いられる差動線路と導波管の伝送線路変換回路を開発している。差動線路の2本の信号線が、正負異符号の電位の信号を有することから、導波管の狭壁から信号線を挿入し、導波管内部電磁界の偏波と平行な電流を、パッチ上に励起する手法を考案している。この手法により高周波デバイスから直接、導波管へ接続することができ、無線システムの低損失化ばかりでなく、高周波回路を測定装置に接続するのにも役立ち、高周波デバイスの測定に広く用いられる可能性のある、汎用性の高い技術である。

以上の成果は、学術雑誌（審査有）論文2編に公表されており、これらの学術的価値から博士論文として十分な内容だと判断される。よって、博士（工学）の学位論文として適格であると認める。