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学位論文題目　A Study on Broadband Transitions of Waveguide and Planar-Line in Multi-layer Substrate at Sub-Terahertz Band
（サブテラヘルツ帯における多層基板内平面線路と導波管の広帯域変換器に関する研究）

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論文内容の要旨

Recent advancements in millimeter wave (mmWave) and terahertz wave (THz wave) technologies have garnered significant interest due to their wide bandwidth, high transmission quality, and potential for enhancing wireless communications. However, challenges such as signal attenuation, obstruction by obstacles, and limited coverage due to short wavelengths persist. To address these limitations, a terahertz (THz) wireless link operating at 300 GHz has been proposed to provide short-range, high-speed wireless services. Significant strides have also been made in THz detection, imaging, and localization applications. Additionally, the application of fifth-generation (5G) technology in robotic surgery and cancer treatment has been explored, along with the use of THz-wave-based sensing technology in the biomedical field. Moreover, advancements in millimeter wave band technology for sixth-generation (6G) communications have enabled data rates of up to 100 Gbps. To meet the growing demand for higher data transmission speeds, developments in interfaces for connection and signal modulation techniques have been pursued. Various antennas and radio frequency (RF) circuits are being developed in the sub-terahertz band, yet the insertion loss of connecting transmission lines remains a serious issue. Therefore, integrating antennas within the dielectric substrate on which the RF chips are mounted is

advantageous. Multilayer substrates are generally used to mount IC chips, allowing space for a large number of signal lines, control lines, and power supply lines.

System-in-package (SiP) technology, which integrates all electronic components into a single package, is experiencing rapid growth to meet the demand for cost-effective and compact radio frequency (RF) modules. Similarly, antenna-in-package (AiP) technology, which integrates antennas and RF transceivers, offers advantages such as reduced delay, high speed, miniaturization, and cost-effectiveness. AiP exhibits significant potential in millimeter-wave bands due to their short wavelengths. The interconnection aspect of the antenna-in-package is critical in influencing RF circuit performance. Proposed approaches, including transitions implemented within packages, have the potential to achieve wide bandwidths, particularly in multi-layer substrate packages. Various functions can be provided to the antennas with the feeding circuits. By applying a beam-forming circuit to the antenna, multi-beam, and beam-scanning functions can be performed. It is effective to locate the feeding circuit on the back of the antenna to realize a compact RF module. Various circuits connecting the transmission lines in different layers have been developed. A microstrip line (MSL) is popular for composing array antennas, and design techniques for various microstrip array antennas have already been established. However, a microstrip line is typically located on the top plane of the multi-layer substrate due to its open structure. A substrate-integrated waveguide (SIW) has become popular as a replacement for a solid waveguide in a substrate. An SIW is generally a low-loss transmission line and can be formed in any layer of the multi-layer substrate due to its closed structure, in contrast to the MSL. An SIW is useful for feeding circuits on the back of microstrip antennas. Transitions play a pivotal role in various applications. Planar microstrip-to-waveguide transitions are commonly employed in waveguide connections between integrated circuits (ICs) and horns and in the measurement of transmission lines without the need for probe stations.

This study presents a broadband planar line-to-waveguide transition in multi-layer dielectric substrates within the terahertz-wave band. The design technique focuses on wideband and low-loss transitions in the sub-terahertz band, providing a comprehensive solution for addressing feeding circuits from IC chips to array antennas. Three main objectives were identified and developed: broad-wall-inserted microstrip-to-waveguide transitions (including single-end and differential-line-to-waveguide transitions), narrow-wall-inserted microstrip-to-waveguide transitions, and SIW-to-SIW transitions in multi-layer substrates. The proposed transitions feature eight copper patterns with a conductivity (σ) of 5.8×10^7 S/m, and a copper plate thickness of 15 μm with a variation of less than ±7 μm. A seven-layer dielectric substrate, HL972LF-LD (Mitsubishi Gas Chemical Company, Inc.), with a dielectric constant (ε_r) of 3.5 and a loss tangent (tan δ) of 0.003, was used. Three prepreg layers with copper were placed on both sides of the center core layer, forming seven dielectric layers. The thicknesses of the core and prepreg substrates were 100 μm and 30 μm, respectively. The thickness variation of the core layer is less than ±15 μm, and the variations of the prepreg layers are less than ±10 μm.

The broad-wall-inserted microstrip-to-waveguide transition is crucial for linking planar transmission lines to waveguides, optimizing power transmission, and minimizing loss. These transitions, designed for both differential and single-ended lines, mitigate loss and achieve wideband performance. While single-ended transitions use grounded suspended coplanar waveguide (GSCPW) and grounded coplanar waveguide (GCPW), and differential transitions use GCPW. These transitions are analyzed through electromagnetic simulations and validated experimentally within the WR-3 band (220 GHz-320 GHz). Corrugation structures are introduced to extend the bandwidth of GSCPW-to-waveguide transitions in a multi-layer dielectric substrate, enhancing transmission characteristics. The proposed transition achieves bandwidths of S_{11} below −10 dB and S_{21} higher than −3 dB, measuring 58.9 GHz and 52.8 GHz, respectively, with corrugations increasing bandwidth by up to 12.2%. Additionally, a GCPW-to-waveguide transition covering the 250-290 GHz band uses a GCPW line and double rectangular stacked patch, achieving a bandwidth of S_{11} below −10 dB of 49.0 GHz. A broadband waveguide-to-differential-line transition with a triple-stacked patch is proposed for the 300 GHz band, involving differential signal lines, and optimized via hole arrangements to prevent electric field leakage and enhance transmission. The measured result shows a bandwidth of S_{11} below −10 dB exceeding 100 GHz and bandwidths of S_{21} higher than −3 dB, measuring 63 GHz.

The narrow-wall-inserted microstrip-to-waveguide transition is crucial for compact transitions, enabling direct connections to waveguide-fed antennas placed closer than $\lambda/2$ apart. This design is ideal for closely arranged waveguides in an array or multi-beam antennas linked to a 2D beam-scanning system. When the microstrip line is positioned on the narrow wall, the probe becomes orthogonal to the E-plane, resulting in limited coupling. To address limited coupling, a modified V-shaped patch replaces the rectangular patch. A broadband tapered GCPW-to-waveguide transition was designed for the 270 GHz band within multi-layer substrates, meticulously crafted to meet the fabrication constraints of the metal pattern and via-hole arrangement specific to the sub-terahertz band. The broadband operation was achieved through a combination of stacked patches and multiple resonance techniques within the cavity. Excitation of the modified V-shaped patch was realized through a tapered GCPW feed line inserted from the narrow wall of the waveguide, transforming the mode from a single-end line to a waveguide and fostering strong coupling between the signal line and the radiating patch. Simulation results indicated a bandwidth of reflections below −10 dB measuring 63.25 GHz (22.7%). The measured bandwidth of reflections below −10 dB extended to 71.50 GHz (26.1%), with an insertion loss of 2.5 dB at the design frequency of 270 GHz. Furthermore, the measured result shows a bandwidth of transmission coefficient higher than −3 dB, measuring 48.60 GHz.

In addition, Substrate integrated waveguide (SIW) is a promising choice for developing millimeter and terahertz wave circuits and components due to its low loss, easy fabrication, cost-effectiveness, and design versatility. It accommodates active and nonlinear elements like surface mounted MMICs, broadening its applications. However, integrating SIW with structurally different components can cause loss and mismatches, making transitions crucial for achieving impedance and field matching between SIW and planar circuits. In this context, a broadband transition has been developed to connect two SIWs formed in different layers of a multi-layer substrate, facilitating the connection between an SIW-fed Rotman lens and an SIW slot array antenna at the 270 GHz band. The transition design was constrained by the fabrication limitations of the metal pattern and via-hole arrangement in the sub-terahertz frequency band. Broadband operation was achieved by combining techniques such as coupled patches, aperture coupling, and a back-short structure. Performance evaluations of the transition were conducted through both simulations and measurements, utilizing waveguide measurements for evaluation. Simulations of the multi-layer SIW-to-SIW transition showed a reflection coefficient bandwidth of less than −10 dB at 73.8 GHz, with a transmission loss of 0.7 dB at the center frequency of 270 GHz. A WG-to-SIW-to-SIW transition with a back-to-back configuration was designed, fabricated, and measured in the sub-terahertz band. The measured results transmission coefficient for a single multi-layer WG-to-SIW-to-SIW transition was −1.8 dB at 270 GHz. Furthermore, the measured result shows a bandwidth of transmission coefficient higher than −3 dB, measuring 57.4 GHz. The measured results revealed a reflection coefficient bandwidth below −10 dB of 64.0 GHz (22.8%), spanning from 248.0 GHz to 312.0 GHz.

This dissertation comprises six chapters. Chapter 1 describes the background and motivation of the study, while Chapter 2 explains the basic theories behind transmission lines and transitions. Chapter 3 presents a broadband broad-wall-inserted planar-line-to-waveguide transition designed for sub-terahertz frequencies within multi-layer substrates. Chapter 4 introduces a broadband tapered GCPW-to-waveguide transition designed for the 270 GHz band within multi-layer substrates. Chapter 5 discusses a broadband transition between two SIWs formed in different layers of a multi-layer substrate at the 270 GHz band. The performances and contributions of the proposed transitions and techniques are concluded in Chapter 6.

論文審査結果の要旨

ミリ波・サブテラヘルツの技術は、次世代高速大容量移動通信6Gや、自動運転等に必要な高分解能センシングなどに、幅広く拡大する応用に必要となる技術である。ところが、このような高い周波数では、高周波伝送線路の損失が大きくなるため、適切な伝送線路を使い分ける必要がある。平面線路は薄型にできるため、携帯端末やさまざまな無線装置への搭載に適しており、集積回路の実装や、平面アンテナの形成などに広く用いられている。その一方で損失が大きいため、長距離を配線するのは、低損失な導波管が適しており、測定装置との接続や、レンズアンテナやホーンアンテナなどの高利得なアンテナの給電などに用いられている。これらの平面線路と導波管という異なる伝送線路を接続するためには、単に特性インピーダンスが等しくなるように伝送線路の形状を設計しておけば良いというわけではなく、伝送線路の形状によって形成される電磁界分布である伝送モードの変換を行う必要がある。さらに、用途によっては、広帯域にわたって、低損失にモード変換する必要があり、これは伝送線路や接続部分の形状や接続方向に大きく依存するため、その形状ごとに設計技術が必要となる。本論文では、集積回路の実装に用いられる多層基板に構成された平面線路と、導波管の伝送線路変換回路および、多層基板内の異なる層に構成された平面線路を接続する伝送線路変換回路について開発した成果をまとめている。

まず、平面線路の信号線を、導波管の広壁側から接続する伝送線路変換回路について議論している。変換回路の広帯域化技術として、第一に、伝送帯域内で、不要な共振の発生原因となっている電流を打ち消すために、金属パターンにコルゲーションを設ける手法を提案している。これにより、コルゲーションの長手方向には電流が流れるため、不要共振の周波数以外の伝送特性には影響を及ぼすことなく、コルゲーションを横断する方向の電流を遮断することにより、不要な共振の発生を無くし、広帯域な伝送特性を実現した結果を報告している。広帯域化技術の2つめとして、対向する差動線路の平面線路を対象として、多層型のリング状のスロットを多層基板内に設けることで、3重共振を実現し、超広帯域な伝送特性を実現している。

次に、平面線路の信号線を、導波管の狭壁側から接続する伝送線路変換回路について議論している。この場合には、導波管の伝送モードと信号線が直交するため両者の結合を促す構造が必要となる。そこで、多層基板内にV形状のパッチアンテナを構成することにより、効率よく電磁波を伝送することができ、さらに方形のパッチアンテナを2重に追加することにより3重共振を発生させ、これにより超広帯域伝送特性を実現している。

異なる層に構成された基板内導波路間を接続する伝送線路変換回路では、両者の結合開口に形成されたパッチアンテナと、ビアホールの配列レイアウトと、バックショート構造を最適化することにより、広帯域な伝送特性を実現した成果をまとめている。

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）の学術論文として適格であると認める。