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学位論文名	Difference Frequency Generation in Microwave/Millimeter-Wave Rectangular Waveguide Embedded with Nonlinear Optical Crystal and Its Applications （非線形光学結晶を充填したマイクロ波／ミリ波帯方形導波管における差周波発生とその応用）
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論文内容の要旨

Millimeter-wave/THz-waves are attractive for many fields such as broadband communications, imaging, sensor, radar, astronomy, and so on. Millimeter-waves/THz-waves are electromagnetic waves at boundary between the light wave region and radio wave region. Therefore, the techniques for the millimeter-wave/THz-wave generation are difficult and have been intensively researched. Nowadays, Difference frequency generation (DFG) based on the second order nonlinear optical effect is one of the potential techniques for the microwave/millimeter-wave/THz-wave signal generation because it is possible to generate a signal at a desired frequency by simply adjusting the frequency difference between the two input lightwaves. Furthermore, the generated power level increases as frequency increases. However, the current DFG devices are usually based on the bulk nonlinear optical crystal without the circuits for generated microwave/millimeter-wave/THz-wave signals. There are some factors that make the conversion efficiency low such as difficulties in controlling the characteristics of the generated microwave/millimeter-wave signal and in the signal coupling. Research of DFG with circuits for the generated signal is required to solve these remain issues for further applications. This thesis describes my study on microwave/millimeter-wave generation based on DFG in a rectangular waveguide embedded with the nonlinear optical crystal. This fusion of the nonlinear optical crystal and the microwave/millimeter-wave rectangular waveguide is a potential candidate for solving the remain issues of the current DFG devices. This thesis is constructed as following:

Firstly, the DFG in the rectangular waveguide embedded with the nonlinear crystal is presented. The characteristics of the DFG signal in a rectangular waveguide embedded with nonlinear crystal are analyzed by using the coupled-mode theory. These fundamentals are necessary for designing new microwave/millimeter-wave signal generation devices.

Secondly, a new microwave/millimeter-wave signal generation device using DFG in a $LiTaO_3$ rectangular waveguide is proposed. A periodically-poled structure is utilized to obtain quasi-phase-matching (QPM) between the lightwaves and the generated microwave/millimeter-wave signal. Characteristics of the device and its application to high frequency signal generation up to THz are also analyzed. In the experiment, the proto-type

of the QPM device is designed and fabricated at the frequency of 15 GHz. The microwave signal is successful generated at the designed frequency from the fabricated device. The measured frequency response of the device was in good agreement with the theoretically expected frequency responses. The experiment results confirm the theoretically expected characteristics of the proposed device.

Thirdly, I propose a new DFG-based microwave/millimeter-wave signal generation device with the phase matching (PM) technique. The dispersion characteristic of the rectangular waveguide is utilized to obtain the PM condition between the input lightwaves and the generated microwave/millimeter-wave. An optical waveguide is utilized for diffraction-less light propagation through the device. The device has a very simply structure. The conversion efficiency is improved $\pi/2$ times compared with the QPM device. By reducing the cross sectional size of the rectangular waveguide, the operational frequency can be shifted to a higher frequency range with keeping the PM condition. A PM device operated at 25 GHz is designed and successfully fabricated. DFG experiment for generation of the 25 GHz signal from the fabricated device is also demonstrated.

Fourthly, application of the proposed DFG-based devices to the optical signal correlation is presented. Two optical waveguides are utilized for launching two lightwaves to the DFG-based device, simultaneously. Two microwave/millimeter-wave signals are generated by DFG in two optical waveguides at the same time. Correlation of the two optical signals is performed in the microwave/millimeter-wave frequency ranges by DFG. Input lightwave coherences and spatial lightwave overlapping are not required.

Finally, the microwave/millimeter-wave circuits for improving the signal output from the DFG-based devices are presented. The microwave/millimeter-wave signal transmission characteristics inside the device and the microwave/millimeter-wave signal emission from the end of the device to the air are analyzed by using the 3-D electromagnetic field analysis. Based on these microwave/millimeter-wave characteristics of the devices, the new structures using a small hemisphere lens and horn-shaped waveguide for the coupling are proposed. The improvement of the coupling can be up to 40 dB with keeping the good resonator characteristics of the device.

論文審査の結果の要旨

マイクロ波からテラヘルツ波にいたる電磁波は，通信や計測，医療など様々な分野で利用されている．それに必須なコヒーレントな電磁波の発生は，通信の歴史そのものであり，発振可能な電磁波の周波数は年ごとに高くなり，現在ではテラヘルツ領域にまでおよんでいる．本論文では，マイクロ波からテラヘツ波までにいたるコヒーレントな電磁波の非線形光学効果による差周波発生について，方形金属導波管内に非線形誘電体媒質を充填した構造を用い，詳細な理論的検討を行い，デバイスの作製，動作の確認，さらにその応用について検討を行った結果をまとめたものである．

非線形光学効果を利用した差周波発生に関する報告はこれまでに多く行われているが，バルク結晶を用いたものが主であり，発生した電磁波の出力を制御することが困難であった．本論文では方形金属導波管内に非線形誘電体媒質を充填した構造を利用するため，応用に際しても有用である．差周波をえるための２光波を変調された光波とすれば，光検出器を用いることなく，マイクロ波からテラヘルツ波までの電磁波を直接検出でき，第６世代の光通信システムに利用されるQAMなどの多値変調方式デジタルコヒーレント光伝送での変調信号が直接検出可能で，ミキサーや電気回路が不要となる．

本論文では，まず方形金属導波管内に非線形誘電体媒質を充填した構造における差周波発生について結合モード理論に基づき議論し，その基礎原理に述べている．ついで，非線形媒質として$LiTaO_3$を取り上げ，マイクロ波／ミリ波発生デバイスを提案している．ここでは，光波とマイクロ波／ミリ波間の準位相整合を得るため，周期分極構造を利用している．信号波発生のための詳細な解析を行い，周波数15GHzで動作するデバイスを設計し，それに基づいたデバイスを作製し，動作確認を行っている．得られた実験結果は予想された結果と良い一致をみている．さらに，方形金属導波管の分散特性を用いた位相整合に基づいた差周波発生を論じている．非線形媒質内をビームとして伝搬させるのではなく，光導波路内を伝搬させた光波と発生させる電磁波との結合を考え，テラヘルツ波まで発生可能であることを示している．周波数25GHzで動作するデバイスを作製し，動作を確認している．また，位相整合型差周波発生の応用として，２つの変調波信号の相関をとるデバイスを提案している．相互コヒーレンスや光波の空間的重なりを必要とせず，容易に相関を取れる特徴を有している．さらにまた，方形金属導波管からの差周波信号出力方法についてレンズやホーン設置による手法を検討し，その有効性を計算により確認している．

以上のように，本論文は，方形金属導波管内に非線形誘電体媒質を充填した構造を用いた差周波発生法を提案し，光通信システムや計測技術の発展に大きく寄与するものであり，博士（工学）の学位論文として十分価値あるものと認める．