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主 論 文 の 要 旨

論文題目 Study of Terahertz Sensing Applications using Metal Structures（金属構造体を用いたテラヘルツセンシング応用に関する研究）

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論 文 内 容 の 要 旨

Terahertz (THz) radiation is the electromagnetic wave roughly between 0.1~10 THz, with its frequency region sandwich between the millimeter wave and infrared wave (wavelength of 3 mm~30 μm). It has several unique characteristics including moderate penetration of many packaging materials, such as paper, cardboard, semiconductors, textiles, plastics, wood, ceramics, dried or frozen materials; the convenience of collimation or focusing by mirror, lens, and other optical elements similar to the infrared wave; additionally, many materials have been proved to possess their specific THz spectra which is nominated as "fingerprint spectra", due to the vibration of molecule; furthermore, it is relatively safe to be applied for bio-related applications because that unlike X-ray, THz radiation is non-ionizing. With all of these amazing advantages, THz applications have been greatly expected, especially in the field of nondestructive inspection and remote identification.

However, for nondestructive inspection application, the direct measurements of THz radiation in some cases can't provide enough sensitivity to observe the tiny variations of the samples. To solve such problem, a 2D metal film with periodic square opening structure (metal mesh) is applied in my research for increasing the sensitivity of the nondestructive inspection measurements. With its unique transmission characteristic in THz region, the change of surface condition of such metal structure like permittivity or refractive index can cause its transmission spectrum a sensitive variation. By mounting the sample onto it, a metal mesh can be considered as a THz sensor for high sensitive measurements.

For remote identification application, the most widely used systems in the past include radio-frequency identification (RFID), the barcode, and more recently, the quick-response (QR) code. The principle of these techniques is communication via reflected electromagnetic waves from encoded elements; however none of these techniques meet the rapidly developing need for industrial applications because barcodes and QR codes only operate at visible wavelengths, which have security implications as well as negative impacts on the aesthetics of the products they identify. Although RFID is suitable for remote operation via a tag that can be concealed and does not require direct human interaction, implementation is expensive and has environmental issues because of the metals and semiconductors used. There has been some recent progress in developing chipless RFID tags to reduce the cost; these solutions essentially entail placing a metal structure on substrate, allowing a spectral response at a few gigahertz. Thus, challenges remain in terms of the complicated design of RFID tags and problems with counting multiple samples because the responses of tags can overlap when they are close in proximity due to scattering of the beam. On the other hand, with the efforts of design, metal (metal-like medium) structures have great potential for operating as THz tags/barcodes for remote identification due to the penetration ability and good directive property of THz radiation.

The research work of exploring the potential applications for terahertz radiation using metal structures, including the THz nondestructive inspection and remote identification over obstacles are presented in this paper. Measurements and their corresponding theoretic calculations are conducted and discussed to support the validity of those works.

Contents of each chapter from my doctoral thesis are concluded as follow:

Chapter 1 Introduction

In this chapter, the background, motivation, and compositions of the doctoral thesis are well stated. The advantage of terahertz radiation and its application is firstly presented. Next, the challenge of the terahertz sensing application is demonstrated by the stationary ink measurements, in which the motivation of this study is presented: the idea of applying metal structure as the sensor for improving the sensitivity of measurements.

Chapter 2 Experimental systems for terahertz wave generation and detection

In this chapter, the experimental setups used for the measurements introduced in later chapters are presented firstly. Terahertz time-domain spectroscopy (THz-TDS) is a well-developed and widely applied approach in the terahertz research field all over the world. The work that author have contributed are mainly achieved by applying THz-TDS with transmission or reflection geometry. Next, the study of cross-polarization effect of the parabolic mirror is presented. Due to the popularity of the parabolic mirror as an optical element in many experimental setups applied for terahertz research, it is urgent to aware the researchers in the terahertz field that the imperfectness of parabolic mirror for keeping the polarization of incident beam. Both theoretical calculation and measurements were conducted with their results presented in this chapter, to demonstrate the cross-polarization effect it can apply to the incident electromagnetic field. At last, conclusion and advices are provided for restraining cross-polarization to its minim level.

Chapter 3 Terahertz component analysis using metal mesh structure

In this chapter, the image of metal mesh that we were using is presents firstly, followed by reporting the incident angle dependence as well as polarization dependence of the abnormal decline band distinguished as "dip" in its transmission spectrum. Several theoretic hypothesis including Surface Plasmon Polariton (SPP)、the Composite Diffracted Evanescent Wave theory, that trying to explain the transmission property of metal mesh are introduced. Interference of diffracted evanescent wave of square opening in (1, 1) direction and the incident wave can cause the extremely high transmission peak in spectrum, which is supported by the comparison between the theory and measurements. Although there is no decisive conclusion to the explanation of transmission property especially the appearance of dip frequency, we believe that the diffracted evanescent wave theory with further modification can be the key to the answer of this question. Next, a series of measurements of human skin (stratum corneum) by applying a THz sensing method using metal mesh are introduced. Two important compositions: intermolecular lipid substance and protein are investigated by applying THz-TDS. We confirmed that quantitative variation of lipid content in stratum corneum sample can be observed sensitively. The protein denaturation is also traceable by using our THz sensor. As a result, we can say that our THz sensing method using metal mesh is a practicable and sensitive spectral analysis for human skin measurements, which may leads to many bio-relevant applications.

Chapter 4 Identification over obstacles using terahertz tags/barcodes

In this chapter, the application of identification over obstacles using terahertz tags/barcodes is explored. Firstly, a metal structure named as the surface metal antenna array (metafilm) is considered for encoding the information. A "clock" shaped mode has been designed and demonstrated in the section 2, along with the measurements and simulations to support its validity. The shift of resonance frequency in reflection spectrum can be considered in proportion to the intersection angle between two metal bars connecting outer ring and inner circle of the "clock" shaped design. This fact shows the simplification of our design for encoding the information. By increasing the number of the metal rings in such design, new resonance peak can appear in lower frequency area, which could be used for carrying more information in one pattern. However, the inconvenience and high cost in manufacture of such metal structure (minimum feature of 10 μm) hold back its potential for the application. Next, the imaging of 1D barcode with conductive carbon ink is considered as the alternative approach for identification application. An issue needs to be well addressed that the higher frequency the better definition of the image, while the absorption of the paper gets larger along with the increasing of frequency. A double-side printed barcode structure is proposed and measured for the purpose of solving the problem mentioned above to achieve remote identification through a package material (EMS envelope). The favorable performance of proposed structure is acquired by comparing it to a simple single-side printed barcode using THz-TDS. So far, the imaging of barcode with minimum feature of 1 mm is acquired by a conventional THz-TDS with soft focused beam (beam size bigger than 1 mm). With the theoretic analysis, we proved the validity of such fully printable barcode structure for the application in real field.

Chapter 5 Terahertz interferometry by applying metal meshes

In this chapter, a new THz interferometric sensor working in the frequency band under 1 THz is proposed. A sandwich structure was chosen and proved to be reliable to form such an interferometer by the measurements of quartz. Then a few samples including polypropylene films、 fingerprint and stratum corneum stripped by tape were measured too. The experimental results suggest that the proposed sensor has the potential to be a sensitive approach for THz sensing applications. For the measurements of stratum corneum and fingerprint, more work need to be repeated with the quantitatively defined samples.

Chapter 6 Summary

In this chapter, it concluded my study by summarizing each chapter of the doctoral thesis.