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主　論　文　の　要　旨

論文題目　**A study on carbon nanotube based nano-mechanical signal receiver (カーボンナノチューブ機械振動子を利用したナノスケールアンテナ)**

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論　文　内　容　の　要　旨

This thesis reports about the first demonstration of digital signal transmission with CNT-based nano mechanical receiver and our related studies with the demonstration.

In chapter 1, we show the background and motivation of this study and introduce the related previous researches to emphasize the significance of our work. By the developing internet of things (IoT) and self-driving technologies, the detection and processing of a large amount of ambient information are important missions. In these technologies, the more sensing devices are expected to be mounted to achieve the much further multiple functions. However, the spatial resource for installing these sensors is finite and is going to face the limitation in almost applications. One candidate of simple approaches toward a resolution of the problem is downsizing the sensors. However, it is difficult to compact all elements especially in a receiver to small sensors because the size of signal receiver depends on the wavelength of incoming signal in electromagnetics. The micro/nano mechanical oscillator have potential for overcoming the restriction of electromagnetics. Although there are some previous researches about small mechanical oscillator, they have focused on fundamental physics and some researches for applications have been progressed based on numerical and theoretical investigations. Thus, the experimental demonstration with the nanomechanical receiver for applications is significant and useful knowledge to connect between basic and applied studies. Therefore, the purposes of this work are proposition of CNT-based original nanomechanical signal receiver, first experimental demonstration of digital information transmission and performance evaluation with the receiver.

Chapter 2 indicates the fabrication method of the nano receiver and the dependence of electric field enhancement on the surface area of counter electrode. The first purpose of the work is to fabricate the receivers on silicon wafer with conventional micro processing for easy implementation in the future. The fabricated receiver consists of a carbon nanotube-based cantilever. The received signal is obtained by field emission current through the receiver. We conformed that the I-V characteristic of the receiver was in good agreement with the Fowler-Nordheim (F-N) law. Secondly, we investigated the potential for controlling the electric field enhancement by changing anode surface area to decrease the driving voltage of the emitter. The surface area of anode is increased by changing its width and numbers of corrugations. The experimental results indicated that the field enhancement on the tip of CNT increased with enlarging surface area.

Chapter 3 introduces that the influence of ambient environment on the performance of the receiver. As one of the most fundamental disturbances, we investigate about the effect of temperature. The mean and variance of field emission current from the receiver increased with increasing temperature. In the current measurement applying constant DC voltage, we found that distributions of field emission current are expressed by Gauss distribution. Based on the experimental results, the dependence of mean and variance of field emission current on temperature are numerically modeled. Utilizing the models, the performance of the receiver was theoretically calculated in terms of temperature. As the results of the performance estimation, the bit-error-rate drastically degraded from $\sim 10^{-9}$ to $\sim 10^{-3}$ with increasing temperature from 325 K to 425 K.

Chapter 4 is the most important in this thesis because the essence of digital information transmission with the nano receiver are introduced. Based on the obtained fabrication and measurement techniques in previous chapters, we transmitted the digitally amplitude modulated color image data to the nano receiver. Combining error correction by encoding with the demonstration, we challenged to first demonstrate of digital communication and evaluate the performance of the nano receiver. The receiver succeeded to receive the image data within only 28 bits errors (total bit number is 393,216 bits). Furthermore, we investigated the dependence of channel capacity on signal gain of the transmitted signal. The receiver exhibited the great performance near theoretical limit with encoding and larger than 2.25V signal gain. These results showed the nano receiver has excellent potential as radio wave receiver.

The nano receiver shows nonlinear output because the received current follows the F-N law. The nonlinearity decreases dynamic range of the receiver. Thus, in chapter 5, we investigated original signal processing method to linearize the output for enhancing the dynamic range. At first, we confirmed that the received signal based on field emission currents consists of even harmonics. Focusing on the harmonics, we combine them with optimally controlled weights to linearize the distorted output. In simple experimental demonstration, we used the 2nd and 4th harmonics as combined elements. The combination with optimally weight resulted in the improvement of nonlinearity error from 14.1 to 8.94×10^{-3} %FS, and increased the dynamic range by 9.6 %.

Chapter 6 proposed the improved fabrication method of the nano receiver. Previous researches have utilized and fabricated one receiver because the nano receivers have been usually fabricated by manual method, and it took long time to fabricate multiple receivers. Although there are some previous researches about alignment and manipulation techniques for nano materials, the methods are also unrealistic to quickly fabricate multiple receivers. Thus, the further development of fabrication method is important for mass production or array receivers. The purposes of chapter 6 are proposition and verification of the original fabrication method for random array receivers (i.e., array without alignment) with the image recognition and machine learning. The image recognition program detected the CNTs in SEM images. Then we automatically obtained the accurate coordinates information of CNTs by machine learning which was learned based on the 1404 SEM images. In almost detected CNTs, the detection errors fell within 200 nm. Based on the detected coordinate data, the original CAD designing program output the designed files for lithography. According to the automation, assuming that we fabricate an array receiver consists of 100 individual receivers, we compressed time for selecting CNTs and preparing CAD from 12 hours to 2 seconds.

Finally, in chapter 7, we summarize achievements of our work and show the remaining problems as future works for serving as a stepping-stone to further development of every related studies. This work succeeded to show the low voltage driven CNT-based nano mechanical receiver, first demonstrate digital communication with the receiver and automate the fabrication process. Although there are remaining works for progressing this study (e.g., the communication demonstration and estimation at resonant mode, uniformalization of array receivers), we believe that our work in present step are extremely significant and will contribute to further develop the nano receiver-based communication systems.