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**Research Paper**

# Theoretical Study for the ITO/Si based High Contrast Grating Structure with Focusing Capability and its Fabrication

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**Abstract** High contrast grating (HCG) is the structure made up of the sub-wavelength grating of high-index and the surrounding layer of low-index, which reveals high contrast between two materials. Its advantages include high reflectivity over a broad bandwidth, polarization and wavelength selectivity, optical high-Q resonator, and phase modulation. In this work, the HCG structure comprising of indium tin oxide (ITO) and Silicon (Si), for the surrounding layer and the grating layer respectively, was studied. Its theoretical model was established, and transmittance, phase and optical behavior were calculated by rigorous coupled-wave analysis and finite element method. Furthermore, the established structure was fabricated to validate its feasibility. The fabricated structure shows the focusing capability whose length is about 10 μm, and the feasibility of the structure was demonstrated. It is also meaningful that ITO layer can contribute to the fabrication of the HCG structure, leading to enable the structure to be electrical-driven.

**Keywords:** High contrast grating, ITO, Si, Phase modulation, Rigorous coupled-wave analysis, Finite element method

## I. Introduction

A high-index contrast grating (HCG) is a promising structure for developing opto-electronic devices, and its extraordinary properties have been studied widely [1-6]. HCG is a grating structure with a high contrast in the refractive index between the grating and its surroundings, and its scale is sub-wavelength. The sub-wavelength-scale structure and high contrast in the refractive index can the structure exhibit various extraordinary properties. Examples of advantage include high reflectivity over a broad bandwidth [1], polarization and wavelength selectivity [2,3], and optical high-Q resonator [4]. In addition, the phase of diffractive waves can be varied locally by making a non-periodic structure, which enables the focal length and angle of diffracted light to be modulated [5,6]. And low-loss hollow-core waveguide are made with HCG high reflectivity at oblique incident angle [7,8]. Thanks to those various advantages, HCG has been applied to opto-electronic devices such as laser diode and vertical-cavity surface-emitting laser [9-11].

In previous studies, air, oxide, and silicon dioxide ($SiO_2$) mainly have been used in the surrounding layer as a low refractive index material, while Si used for the grating layer as a high refractive index material, which is high contrast with the low index [1-7]. $SiO_2$ has a refractive index of about 1.6 at wavelengths of interest, which is high contrast with the index of Si of about 3.7 at those wavelengths. In this work, indium tin oxide (ITO) was used in the surrounding layer with the grating layer of Si. The study for the HCG structure using ITO and Si has been not yet reported, and it is very meaningful for developing opto-electronic devices due to the characteristics of ITO. The refractive index of ITO is an appropriate value of about 1.8, which has a high contrast with the index of Si. In addition, the surrounding layer of ITO has a significant advantage for the opto-electronic structure, showing an electrical conductivity while the layer of $SiO_2$ is not conductive [12-14]. The conductive layer in the structure enables nano-structure such as laser diode to be electrical-driven. In this work, we validate the feasibility of the ITO/Si based HCG structure by calculating and fabricating the structure having the focusing capability, which was fabricated with Si and $SiO_2$ in the previous work [5].

## II. Theoretical Method and Experimental

The theoretical model of HCG is established in order to calculate and simulate the model's optical characteristics, and to use their scales in experiment. Figure 1 shows the schematic diagram of ITO/Si based HCG we establish. The gratings of Si on the surrounding layer, ITO, were shown, and the thicknesses ($t_h$ and $t_l$) and refractive index ($n_h$ and

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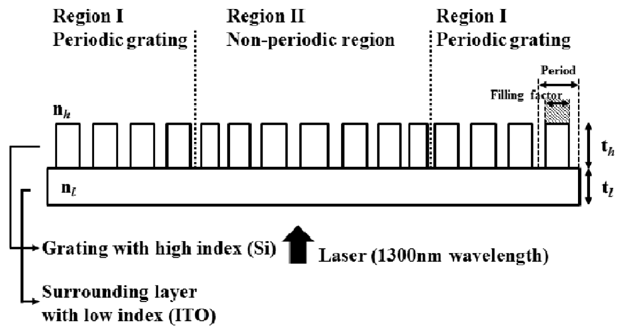


**Figure 1. Schematic diagram of the HCG structure.**

$n_l$) of each layer were indicated in Fig. 1. Also, the period of grating and the filling factor, the ratio of Si to period, were indicated. Region I is the periodic grating structure whose period is uniform, and Region II is the non-periodic grating structure whose period is not uniform. The change of period in this region modulates the phase of diffractive waves, and further, determines a focal length of HCG with focusing ability.

We calculated the transmittance, reflectance and phase of the light with respect to the period and filling factor of HCG by rigorous coupled-wave analysis (RCWA), and those results were depicted in Fig. 2. Figure 2(a) shows the transmittance property at 1300 nm wavelength, and the phase property is not shown for brevity. The values of transmittance from zero to about 100 were obtained, and the significant changes of transmittance are shown at the period of about 600 nm and the filling factor of about 0.40. The consecutive change, needing to the phase modulation, of the phase also is obtained even though not shown in figure. Those changes of transmittance and phase play important roles for focusing ability of HCG. To constitute the HCG structure, we choose the value of filling factor and the range of period. In case of the region I, the period of 620 nm and the filling factor of 0.64 are chosen for the transmittance of about 0.01%. In case of the region II, the filling factor of 0.50 are chosen, and the period from 200 to 800 nm are shown in Fig. 2(b). The transmittance of this region is about 80~90%, and the phase changes with the variance of period also are shown in Fig. 2(b). Using chosen values from Fig. 2, we constituted the ITO based

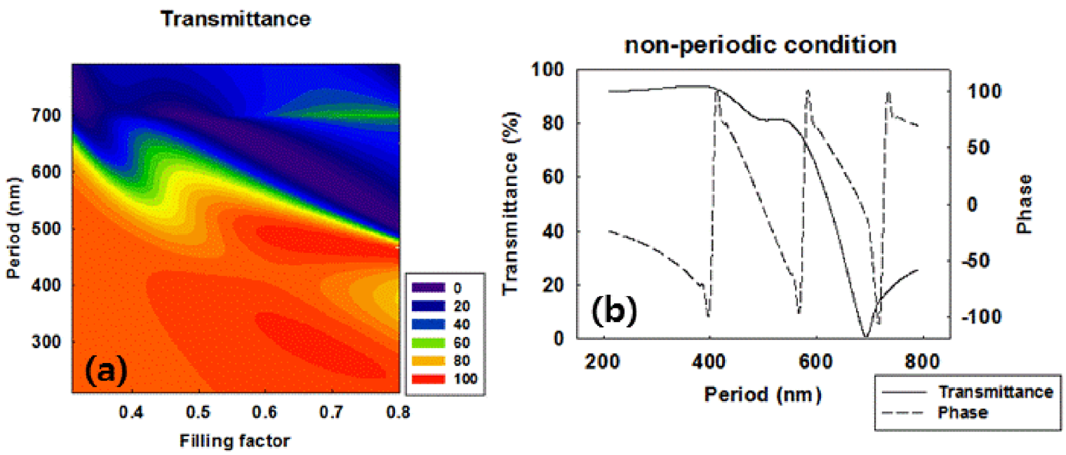


**Figure 2. (a) The two-dimensional plot of transmittance with respect to grating periodicity and filling factor. (b) The chosen parameters for the non-periodic HCG structure from Fig. 2(a).**

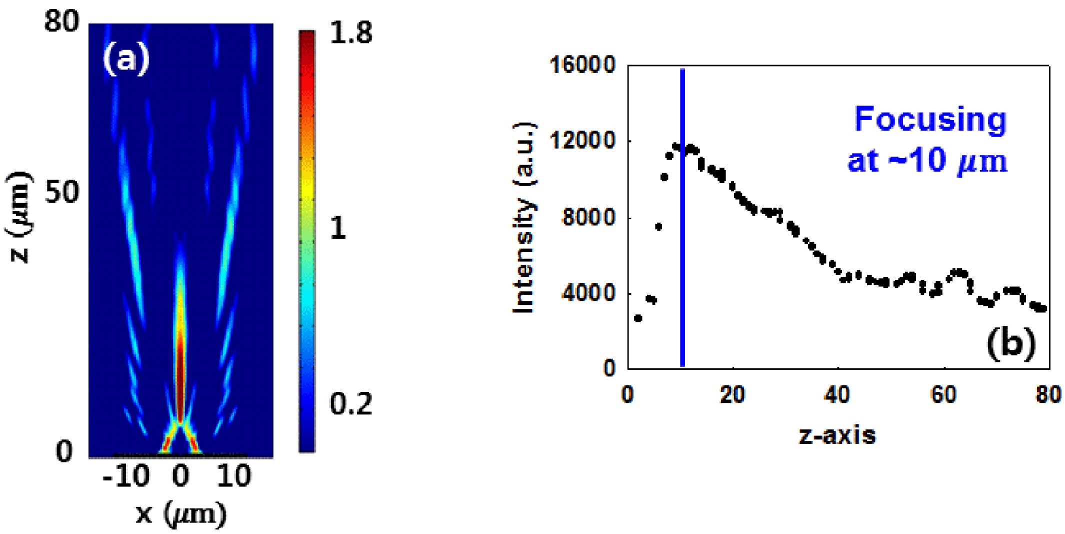


**Figure 3. The results of numerical simulation for the steering capability (a) and their analyzed result (b).**

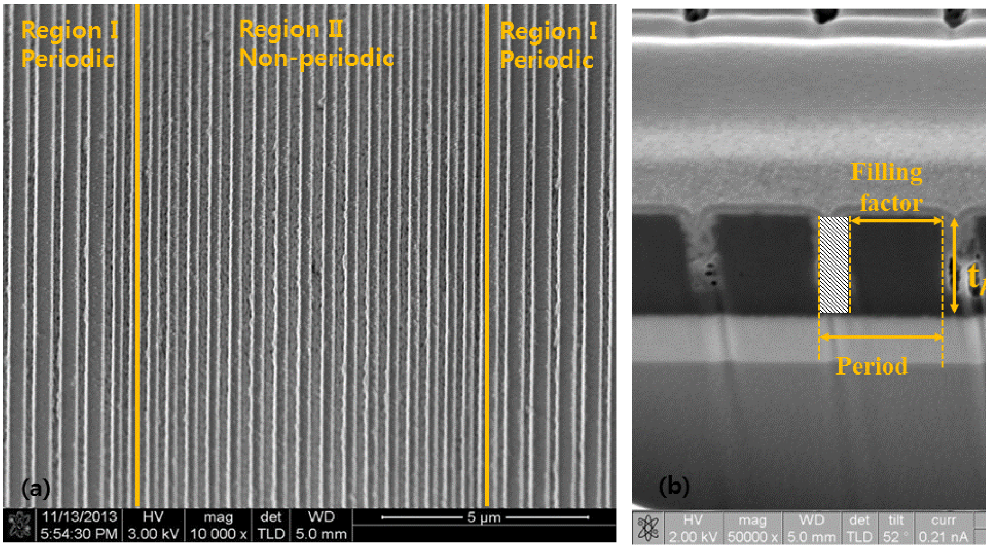


**Figure 4. The SEM image of the fabricated structure at top view (a) and the SEM image using FIB at cross-sectional view (b).**

HCG structure like the schematic diagram depicted in Fig. 1. At the both sides, the periodic grating with low transmittance was located, and at the center, the non-periodic grating whose period varied from 470 to 570 nm with the high transmittance was located. To obtain the behavior of light propagating the constituted HCG structure, we performed finite element method (FEM)-COMSOL-RF module. The results of calculation are shown in Fig. 3. Figure 3(a) shows the result of FEM calculation for HCG with focusing ability, and Fig. 3(b) shows an analyzed data of Fig. 3(a). Figure 3(a) is a visualized data of transmitted light with respect to *x*-*z* position. Transmittance had maximum values at the center position ($x$=0), and the transmittance at the center with respect to *z*-position were shown in Fig. 3(b). The maximum value among those values was located at about 10 μm as shown in Fig. 3(b). These results indicated the focal length of transmitted light was about 10 μm. Theoretical data suggests the ITO/Si based HCG structure may be realized.

To validate the simulated results and realistic possibility, we made the HCG structure established in theoretical approach and simulation. The samples used in this work were prepared on a double polished and semi insulating GaAs (100) with a thickness of about 300 m. By magnetron sputtering method, ITO and amorphous Si were deposited about 245 nm and 535 nm, respectively. The sputtering deposition was performed at Ar atmosphere of $3\times10^{-3}$ Torr and room temperature. The refractive indices and thicknesses of the deposited layers were determined by spectroscopic ellipsometry over the wavelength of interest. The determined values of Si and ITO are 3.77 and 1.85, respectively. And these values were used in numerical simulations and fabrication process. Next, e-beam lithography process was performed. The positive e-beam resist (ER) solutions, PMMA 495 A4 and PMMA 950 A2 were used. These two layers assure to make the accurate shape of grating structure, and developed for about 10 seconds in a solution of acetone. Next, a metal mask process was performed because ER layer had not enough solidity for enduring a deep reactive ion etching (DRIE). Ni layer of about 30 nm and Cr layer of about 70 nm were coated by e-beam evaporator. By etching the ER residue, the metal mask was made on the Si layer. Finally, Si was etched by DRIE with $SF_6$, and the metal mask was removed by YMStech Ni etchant TGF. Au mask was coated in a periphery of HCG structure to prevent unneeded transmitted beam from the periphery. Figure 4 shows a scanning electron microscope (SEM) image of the fabricated structure. As shown in Fig. 4(a), region I and II were identified by showing the structure at top view, and the shape of each grating was checked in Fig. 4(b).

To validate the focusing ability of the fabricated structure, the optical measurement system was constructed. This system includes two charge-coupled devices (CCD), a fiber coupled InGaAs detector, and a fiber coupled laser source with 1300 nm wavelength. An automatic stage with a sensitivity of 150 nm was used due to the fine size of sample. In this system, the intensity of transmitted light with respect to *x*-axis distance was measured with increasing *z*-axis distance. The fiber of InGaAs detector worked by the automatic stage had a velocity of 1 μm/s for *x*-axis, and measured the intensities of 4 points per 1 μm.

## III. Results and Discussions

The results of optical measurement have a good agreement with the result of simulation, and its measured values are shown in Fig. 5. The intensities of transmitted light with respect to *x* and *z* positions were measured. For the measurement of transmitted light with *x*-position, all the measured values have maximum values at the position of $x$=0 which means the center of HCG. Next, by fixing the *x*-position, the changes of transmitted light's intensities are

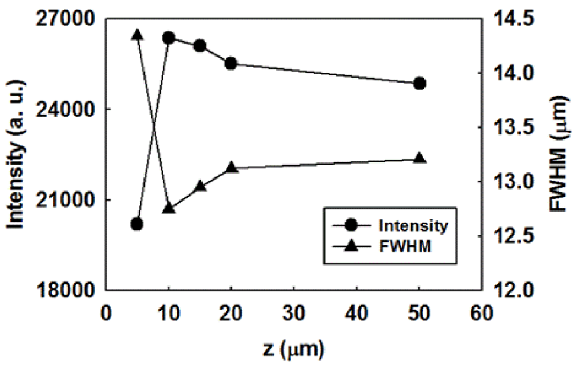


**Figure 5. The experimental result of optical measurement.**

investigated with increasing the *z*-position. In these investigation, the maximum values of intensity were obtained at *z*=10 μm. Also, the full width at half maximum (FWHM) values for the spectra of transmitted light are investigated, it reveals that the minimum values of FWHM were obtained at=10 μm. The results of both intensity and FWHM indicated that the transmitted light was focused at about 10 μm.

Theoretical results and simulation show that the established HCG has a focal length of about 10 μm, and its experimental result has a good agreement with that. This agreement means that the ITO/Si based HCG structure can be realized, and its focusing ability also can be achieved.

## IV. Conclusions

The theoretical model of the ITO/Si based HCG structure was calculated using RCWA and FEM, and it reveals that the focal length of the structure is about 10 μm. In order to validate the feasibility of the ITO/Si based HCG structure showing the focusing capability, the theoretical model was used for its fabrication. In the process of fabrication, the sputtering method was used to deposit the ITO and Si layers with a thickness of 245 nm and 535 nm, respectively. And Si grating structures with a rectangular profile were fabricated by e-beam lithography process. For the periodic HCG region, their periodicity and filling factor were 620 nm and 64%, respectively, and for the non-periodic HCG region, their periodicity varied from 410 nm to 570 nm with fixed filling factor of 50%. The periodic HCG region has the transmittance of 0.01%, and the non-periodic HCG region has the transmittance of 80~90%, whose phase changes make the transmitted light focus its focal length. Fabricated structures showed that the transmitted light had the focal length at about 10 μm, and this result was in a good agreement with theoretical results. This study shows the feasibility of fabrication of the HCG structure using ITO and Si, and its focusing capability also was accomplished. Therefore this study will be helpful for the optoelectronic devices and the optical computation system research.

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