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Optimization of performance parameters of high-contrast subwavelength grating with high reflectivity for bio-sensing applications

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Highly reflective mirror technologies are majorly required in bio-sensing applications to eliminate complex multiple diffraction orders. In this paper, various grating parameters, *i.e.* width, thickness, and period are analyzed to get optimized values and high reflectivity for high-contrast subwavelength grating (HCSG) structure. Besides these parameters, polarization modes, angle of incidences, and refractive index have been diversely analyzed to monitor their effects on HCSG structure with respect to reflectivity. The simulation results manifest that the optimized parameters help to achieve the best reflectivity that can be further utilized in bio-sensing applications.

Keywords: grating parameters, high-contrast subwavelength grating, reflectivity, polarization.

1. Introduction

In optics, optical gratings are very essential building components for a photonic integration platform. They are well-known in two main regimes in which the grating period L is larger than the wavelength λ, which is called the diffraction regime and in which the grating period is much smaller than the incident wavelength, which is called the deep sub-wavelength regime [1]. Although, among these two main regimes exist a third regime known as the near subwavelength regime in which the grating period value lies between the surrounding medium and the grating material's wavelength. In this regime, grating acts distinctively and manifests the many features that do not frequently pertain to grating [2]. During the past few years, a near-wavelength grating structure has been discovered with a high-index medium [3]. When light incident upon gratings with wavelength λ, light is transmitted and reflected according to Snell's law and there exists a field inside the grating that is suitably small enough to eliminate all other diffraction orders except zeroth order diffraction. Sub-wavelength gratings have been used as reflecting mirrors, resonators, and filters. Previously researchers have worked on HCSG (high-contrast subwavelength grating) applications in the field of optoelectronics devices like vertical cavity surface emitting laser (VCSEL), resonators, and reflector due to the elimination of higher-order (non-zero) diffraction in grating [4,5].

Recently, Huang *et al.* [6] proposed effective optical feedback, control of the wavelength and polarization of the incident light for HCSG. With the integration of HCSG on VCSEL, the epitaxial thickness of the VCSEL mirror decreases and further increasing the fabrication tolerance. Chung *et al.* [7] reported the theoretical study of HCSG and their impact on VCSEL as a reflector using different polarizations where HCSG had a large grating thickness and a small grating period as compared to TE mode. Sun *et al.* [8] designed silicon-based HCSG as a resonator for bio-markers for label -free detection. Marciniak *et al.* [9] proposed another subwavelength HCSG as a highly reflective mirror in VCSEL sensitive to the surrounding environment. They showed how the refractive index of the material alters the VCSEL mirror reflectivity. But the study in [9] was presented for 1651 nm wavelength for methane absorption only and detection of other substances is yet to be done. Fang *et al.* [10] demonstrated a polarization-independent filter using an HCSG structure to achieve high reflectivity using grating width, grating thickness, grating periods, and angle of incidence. The value of the grating period, length, and angle of incidence of light decreases and then the reflectivity of the HCSG structure also changes.

The above literature shows that the HCSG structure can serve as a potential platform in VSCEL, resonators, and polarization-independent optical filters because of its large number of applications. But the grating analysis for high reflectivity by optimizing performance parameters has not been done before.

In this paper, we analyze HCSG structure grating parameters deeply to achieve high reflectivity and wavelength shift for biosensing applications. HCSG design is examined for different values of optimized parameters, *i.e.* polarization modes, angle of incidences, grating widths, grating periods, grating thickness, and refractive index and its impact on the reflectivity of HCSG structure. We analyzed that the proposed HCSG structure can be easily designed by using Opti FDTD software instead of numerical calculations and with its optimized parameters it can be easily implemented as bio-sensing applications.

2. Design methodology and analysis

The proposed schematic structure of high-contrast sub-wavelength grating on silicon dioxide substrate with optimized design parameters that affect the reflectivity of HCSG has been illustrated in Fig. 1. The design parameters are comprised of grating and its surrounding materials (index of refraction), grating thickness t_g, grating width S, low index layer thickness t_l, grating period L, and filling factor F.

The filling factor F is defined as the ratio of the width S of the high index material to the grating period L. Refractive index of grating material Si and underneath material SiO_2 are 3.47 and 1.47, respectively. The structure of HCSG based on SiO_2 as

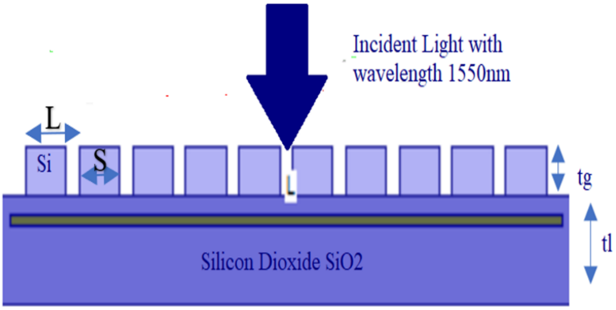

Fig. 1. Proposed structure of high-contrast sub-wavelength grating with normal angle of incidence using wavelength $\lambda = 1550$ nm.

a substrate is 8.5 μm wide with silicon rectangular grating of thickness 0.460 μm. The height of low-index material is 1 μm.

When a normal incident light with wavelength ($\lambda = 1550$ nm) falls on the grating, a small amount of array propagation modes in grating are excited. These propagating modes enter from the plane where $z = 0$ and propagate in a downward direction to the output plane where $z = t$ can be transmitted in the same direction and escape from the output plane or it can be reflected towards the input plane. Light can be reflected and transmitted with zero-order diffraction. Further optimized design parameters that affect the reflectivity of HCSG are analyzed using Opti-FDTD simulation software. In FDTD simulation, a continuous wave is used for excitation of the electromagnetic field in the grating at the wavelength λ of 1550 nm with a 15 nm mesh size.

When the grating period is very much smaller than the input wavelength, zero-order diffraction exists in the grating. When the light of wavelength λ falls on the grating with incident angle θ, the electromagnetic waves are transmitted out and get reflected from the grating. Transverse electric (TE) and transverse magnetic (TM) polarized modes are used as excitation for grating which provides zeroth order diffraction and reflectivity spectrum has been observed for HCSG structure.

3. Simulation results

3.1. Effect of polarization modes on HCSG structure

The proposed structure is analyzed based on various parameters. It has been observed that high reflectance is obtained at one or two wavelength points in TM mode. Table 1

Table 1. Grating parameters at different polarization modes.

Polarization	Thickness t_g [μm]	Grating period L [μm]	Grating width S [μm]	Wavelength λ [nm]
TE	0.460	0.780	0.5860	1550
TM	0.460	0.780	0.5860	1550

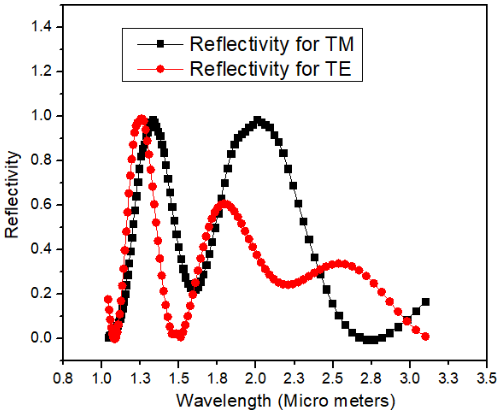

Fig. 2. Power reflectance of HCSG design for TE and TM mode.

gives the values of grating parameters at different polarization modes that decide the reflective characteristics of the grating.

Figure 2 illustrates the comparison of reflectivity for both TM and TE mode obtained with the above-mentioned parameters. It can be observed that high reflectivity of 96–99.9% has been obtained for both modes. However, from the plot, it has been concluded that high reflectivity is obtained for TM mode at wavelengths ranging between 1.26–1.30 µm and 2.01–2.18 µm points.

Whereas for TE mode, only a wavelength range of 1.23–1.29 µm is active due to optimized grating design parameters of HCSG. In the HCSG design for TM mode, the grating thickness should have a large value and the grating period should have a small value for high reflectivity. So, for further optimized parameters, TM mode is used as excitation on the grating surface of HCSG.

3.2. Effect of different angles of incidences on grating's reflectivity

The performance of the HCSG structure in terms of reflectivity has been analyzed by varying the angle of incidences for wavelength range 1.033 to 3.1 µm. Figure 3 represents the power reflectance of the gratings which were simulated using Opti-FDTD software. It can be realized that as the angle of incidence increases, *i.e.* from 0°, 4°, 6°, and 8°, the reflectivity of the grating decreases, and the position shifts towards the longer wavelength, therefore two resonance peaks are observed. From the results, it has been observed that at 0° and 4°, 99.998% reflectivity is achieved.

3.3. Effect of various grating parameters on reflectivity

Simulation has been done for various grating parameters, *i.e.* width, thickness, and period that decide its reflective characteristics. Figure 4(a) depicts the HCSG performance for various grating widths based on power reflectance at 0 degrees of incidence.

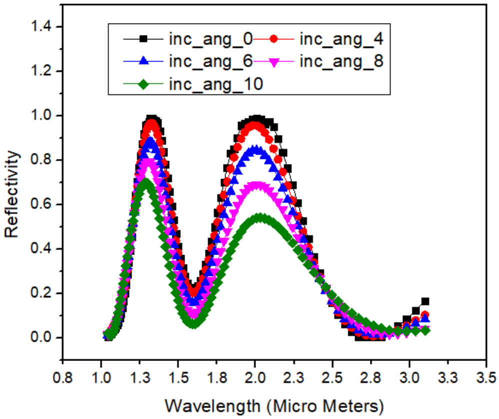

Fig. 3. Power reflectance of HCSG design for different angles of incidence.

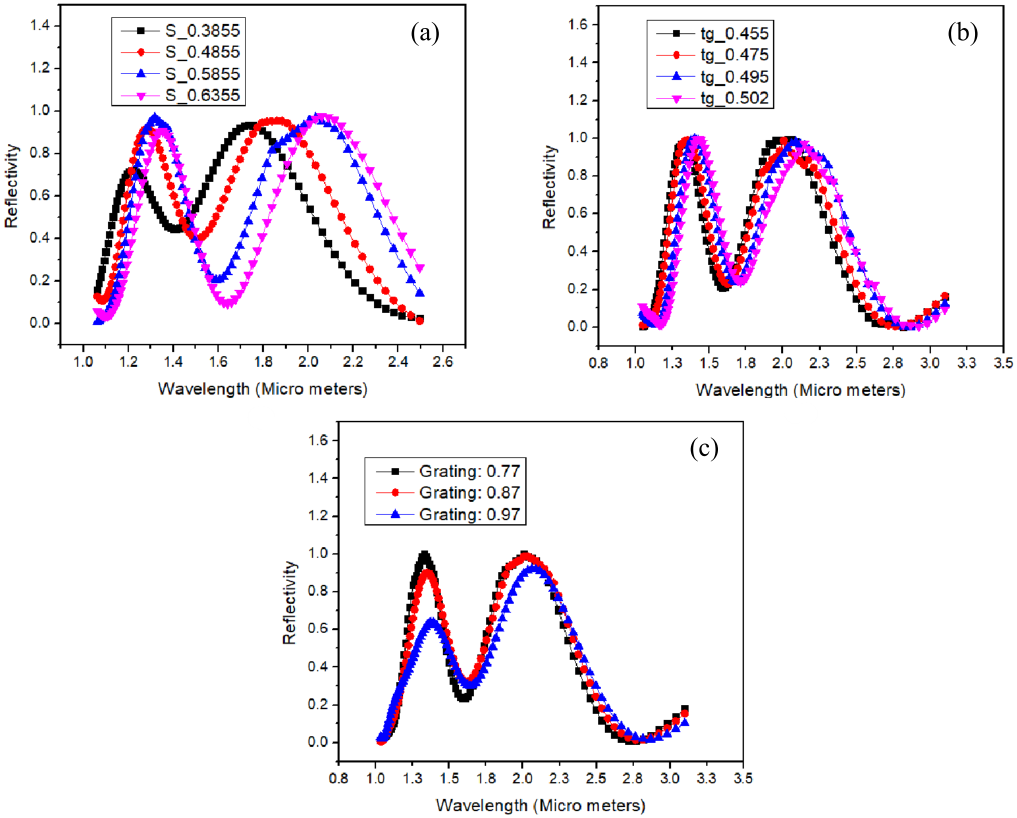

Fig. 4. Plot showing reflectivity *versus* the wavelength for different (a) grating widths, (b) grating thickness, and (c) grating periods.

Alteration in reflectivity can be seen with the increase in grating width *S* from 0.3855 to 0.4855 µm and then changing it to 0.5855 and 0.6355 µm. It is observed that reflectivity increases till a particular value of 0.5855 µm, and after that it decreases to a large extent and there is also a wavelength shift of approximately 0.12 µm towards high wavelength sides.

The plot in Fig. 4(b) represents the effect of thickness on the grating sensor performance. It has been observed that as thickness increases in fashion from 0.455 to 0.475 µm and to 0.495 and to 0.520 µm, the peak values are almost the same, they are at two wavelength points but in different ranges, *i.e.* one between 1.32 and 1.41 µm and another peak in the range 1.91–2012 µm. The wavelength shifts a little toward the right side for different grating thicknesses.

Figure 4(c) depicts the effect of various grating periods on reflectivity: by increasing the grating period of the design structure, the reflectivity decreases in large amounts with small wavelengths shifting toward high wavelengths. Best reflectivity is achieved at 0.77 µm grating period.

3.4. Effect of the various refractive indexes above grating on reflectivity dip

The reflectivity of HCSG has been observed with a different refractive index of surrounding mediums above the grating. Figure 5 reveals the results for HCSG with various

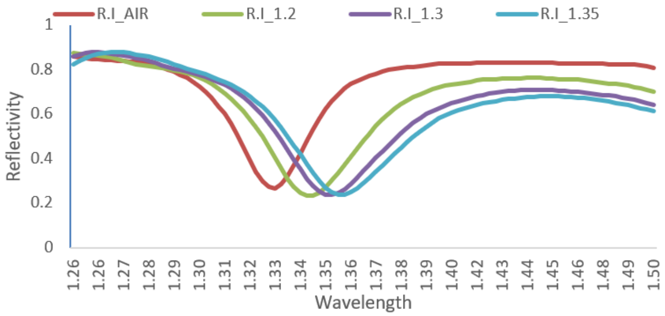

Fig. 5. Reflectivity plot for different refractive indices around the HCSG as a biosensor.

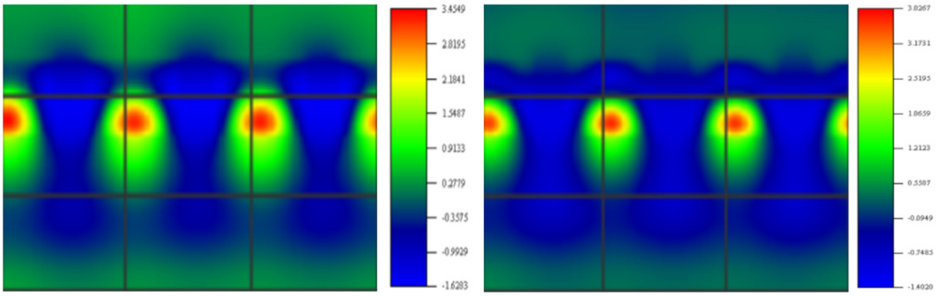
(a) (b)

Fig. 6. Optical field distribution for HCSG for (a) R.I. = 1.0 and (b) for R.I. = 1.2.

Table 2. Comparison of proposed reflectivity with values reported in literature.

	Reflectivity [%]
Reported in [11]	85.00
Reported in [12]	83.20
Proposed	**99.998**

surrounding refractive indices (R.I.) *i.e.* R.I. = 1, R.I. = 1.2, R.I. = 1.3, and R.I. = 1.35. There is a change in wavelength in reflectivity dip due to a change in surrounding refractive index. This property of high-contrast subwavelength grating can be used for biosensing applications.

Figure 6 (a) and (b) shows the proposed results of the light intensity distribution in the HCSG sensor with R.I. = 1.0 and R.I. = 1.2, respectively. It has been observed that light intensity inside the grating decreases with an increase in the refractive index of the surrounding.

The reflectivity of 85% [11] and 83.2% [12] are reported low whereas the proposed structure yields high reflectivity. Hence, the comparative results shown in Table 2 with previously reported literature show the superiority of the structure.

4. Conclusions

In this paper, we presented an analysis of the HCSG structure that has been done to achieve optimization of performance parameters for high reflectivity. The best-optimized parameters in our research for HCSG structure are polarization mode (TM mode), angle of incidence (0°, 4°), grating width ($S = 0.5855$ μm), grating thickness ($t_g =$ $= 0.495$ μm), and grating period ($L = 0.77$ μm). Along with these parameters, as the refractive index of the surrounding material of grating changes, a wavelength of reflectivity dip shifts towards the right side. All these parameters result in 99.998% reflectivity for HCSG structure that can be further utilized in bio-sensing applications.

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