High-Contrast Grating reflectors for 980 nm Vertical-Cavity Surface-Emitting Lasers

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ABSTRACT

This paper presents results of computer simulation of 1D monolithic high refractive index contrast grating (MHCG) reflector also called surface grating reflector (SGR). We analyzed optical properties of the GaAs reflector designed for 980 nm wavelength with respect to the grating parameters variation. We also determined the electric field patterns after reflection from the structure in several cases of parameters variation. We show that thanks to the scalability and design simplicity, proposed design is a promising candidate for simple, next generation vertical cavity surface emitting lasers emitting from ultra-violet to infrared.

Keywords: High Contrast Grating, Surface Grating Reflector, Vertical Cavity Surface Emitting Laser, computer simulation, photonic crystal

1. INTRODUCTION

High refractive index contrast gratings (HCGs) have drawn great attention for several years already. It has been shown that those planar devices can be designed to have almost 100% reflectivity for surface-normal incidence [1]. This feature, together with strong polarization discrimination and sub-micron thickness of an HCG reflector, made it very interesting candidate for a mirror in VCSELs. Extensive studies showed that hundreds of nanometers thick HCG can be designed in such a way that it is characterized by 150 nm spectral range of reflectivity exceeding 99% [2], while the same value for typical, several micrometer, multi-material distributed Bragg reflector (DBR) for the same wavelength is 75 nm [3].

DBR is multi-layer stack of two different, periodically repeated materials. Its reflectivity can be increased with the increase of number of those pairs or with the increase of refractive index contrast between them. Unfortunately, most combinations of materials give low refractive index contrast or high strain between DBR layers. As a result, DBRs consisted of hundreds of layers has to be made or deliberate strain compensating schemes has to be incorporated. Since a compromise between lattice mismatch and refractive index contrast has to be reached, practically only GaAs/AlAs based DBRs can be utilized in VCSELs which are manufactured in a single epitaxial process. Lack of suitable, native DBRs for VCSELs in other material systems vital to optoelectronics, like GaN and InP, creates a need for novel reflectors. One of the approaches is wafer-bonding of dielectric DBRs to GaN or InP resonator. Since the process requires two separate growths of DBRs and additional one of resonator and then rather sophisticated bonding process, it does not seem to be feasible for large scale manufacturing.

In contrary, the HCG is single layer photonic structure composed of periodically repeated stripes made of high refractive index material and low refractive index material gaps between them (Fig. 1a). It has been shown, that in order to provide features described earlier, it has to be surrounded by low refractive index media [4]. This can be satisfied in several

ways: mirror in the form of GaAs membrane suspended in the air [5], Si stripes embedded in silicon-dioxide [6] or placed on the top of the cladding layer made of aluminum-oxide [7] or diamond [8]. The HCG offers very stable polarization and phase control. Another advantage in view of HCG utilization in VCSELs is inherent lateral optical confinement produced by finite size of the HCG [9] which introduce the lateral confinement by waveguiding effect in a manner similar to 2D photonic crystals [10-13].

Fig. 1. a) Schematic view of high contrast grating where L - grating period, F - fill factor or duty cycle, h_{HCG} - HCG thickness or etching depth, n_{low} - low refractive index medium, n_{high} - high refractive index medium, b) schematic view of monolithic high contrast grating.

In the work of Goeman et al. [14] SGR named GIRO-grating characterized by 85 % reflectivity of 1.55 μm TE-polarized light was analyzed. More recently, Lee et al. [15] presented GaN made SGR designed for 0.45 μm , TE-polarized light which showed almost 100% theoretical and 92% experimental reflectivity. Both approaches showed very high reflection from sub-wavelength grating illuminated from the high refractive index material side which, since patterned on a single material, was not interleaved by low refractive index material on both sides of the mirror. Difference in reflectivity from the low refractive index side (air) and high refractive index side (substrate) limits the range of applications of such mirror on one hand and opens new on the other. In case of VCSELs, where light is generated inside the laser, after mentioned disproportion in reflectivity does not create any problems. On the other hand, design of VCSEL based on such MHCG becomes extremely simple, since low refractive index material cladding is no longer needed. In the following section, the computational model used for calculations presented here, is shortly described. In the Third section of this work, results of simulation of GaAs MHCG designed for 980 nm TE-polarized light are presented.

2. COMPUTATIONAL MODEL

The core of our optical module consists of implementation of Plane-Wave Reflection Transformation method (PWRT) which is a modification of Plane-Wave Admittance Method (PWAM) [16]. In general, the PWRT method changes the problem of solving the set differential equations into the problem of finding eigenvalues of a matrix. It solves Maxwell equations in a frequency domain by using a plane-wave expansion within each layer and computes an analytical solution in the perpendicular direction. Such approach is possible due to transformation of the electromagnetic (EM) field to the diagonal coordinates. In particular, the Maxwell equations are first transformed into second-order matrix equations of the form

$$\frac{\partial^2 \vec{E}}{\partial z^2} = -\mathbf{P}_H \mathbf{P}_E \vec{E} \frac{\partial^2 \vec{H}}{\partial z^2} = -\mathbf{P}_H \mathbf{P}_E \vec{H} \quad (1)$$

where $\vec{E}$ and $\vec{H}$ are super-vectors containing Fourier coefficients of the components of the electric and magnetic field functions defined over the computational domain. Matrices $\mathbf{P}_E$ and $\mathbf{P}_H$ are computed by applying lateral differential operators present in Maxwell equations on a set of basis plane-wave functions. Eqs. (2) can be transformed into a set of decoupled equations, which can be solved analytically:

$$\frac{\partial^2 \tilde{E}}{\partial z^2} = -\Gamma^2 \tilde{E} \frac{\partial^2 \tilde{H}}{\partial z^2} = -\Gamma^2 \tilde{H} \quad (2)$$

where Γ is a diagonal matrix of propagation coefficients and super-vectors $\tilde{E}$ and $\tilde{H}$ contain the amplitudes of the corresponding modes propagating in the z -direction. As values of Γ can be real, imaginary, or complex, both the propagating and attenuating modes are considered. In the PWAM, the fields are matched using the admittance transfer technique and the eigenmode is found by searching for a complex frequency that yields a non-zero EM field distribution. On the other hand, the PWRT uses the concept of iteratively determined reflection matrix $\mathbf{R}$, which is defined in each layer as a relation between forward and backward propagating field ($\tilde{F}$ and $\tilde{B}$, respectively):

$$\tilde{B} = -\mathbf{R}\tilde{F} \quad (3)$$

This matrix can be directly used for computation of the reflection coefficient of a mirror or for determination of eigenmodes in VCSEL cavity. For the latter purpose it is sufficient to require that at both bottom and top edges of the laser structure there is no incident field and use the same root-finding algorithm as in classical PWAM. However, there is no need to use vertical absorbing boundary conditions, as both the top-most and the bottom-most layers can be considered as having infinite thicknesses. The PWRT is very computationally effective and capable of finding eigenmodes of any planar photonic structure, and any composition of those.

3. RESULTS

First step of the analysis of the GaAs MHCG presented in this paper was optimization of grating parameters in order to obtain very large reflectivity for 980 nm. For TE-polarized light parameters of the optimal design are as follows: $L = 0.815 \mu\text{m}$, $F = 0.35$, $h_{\text{HCG}} = 0.164 \mu\text{m}$. Fig. 2 shows spectrum of total reflectivity as well as reflectivity of higher diffraction orders if the MHCG is enlightened from the high refractive index side (from the substrate). Constant refractive index of gallium arsenide equal 3.52 and no absorption were assumed. One can notice that for 980 nm reflectivity of zero diffraction order is nearly 100% and all higher order modes are suppressed in the GaAs at the same time. Since the grating is sub-wavelength, all of the higher diffraction orders on the air side of the mirror are evanescent.

Fig. 2. Spectrum of reflectivity of diffracted orders for GaAs MHCG enlightened from the bottom, where $L = 0.815 \mu\text{m}$, $F = 0.35$, $h_{\text{HCG}} = 0.164 \mu\text{m}$, $n_{\text{high}} = n_{\text{GaAs}} = 3.52$ and $n_{\text{low}} = n_{\text{air}} = 1.0$, zero order - solid line, first order - dashed line, second order - dot-dashed line, third order - dotted line.

Following results were obtained assuming dispersion relation and absorption vs. wavelength for GaAs based on [17]. In the Fig. 3a) reflectivity of TE-polarized light (solid line) and TM-polarized light (dotted line) if the MHCG is enlightened from the substrate. Additionally, phase of the TE-polarized light reflected from the substrate is presented (dashed line). It is worth pointing out that the phase of the reflected light is 2π for $1\text{ }\mu\text{m}$, while peak of the reflectivity is centered around 980 nm . Due to this almost 20 nm spectral shift of phase, for 980 nm wavelength, light penetrates the grating and, in case of resonator, shifts the anti-node position of the standing wave slightly from the substrate/grating interface into the MHCG region. Fig. 3b) shows light intensity distribution in close proximity of the optimized grating. Most of the light is enclosed in the top part of the grating stripes. Above the MHCG (in the air) evanescence of the field is clearly visible. In contrary, below the MHCG (in the substrate) reflected wave pattern is formed.

Fig. 3. a) Reflectivity spectrum of the optimized MHCG structure for TE polarization (solid line) and TM polarization (dotted line) and phase at the interface between GaAs substrate and MHCG (dashed line), b) Light intensity distribution near the MHCG surface for TE polarization and 980 nm wavelength.

Next step of performed simulation was to vary one of the MHCG parameters, while two others are kept constant in order to determine design tolerances for manufacturing error. In the Fig. 4 reflectivity of the MHCG with respect to the period L is presented. The 99% reflectivity is sustained for period between $0.767\text{ }\mu\text{m}$ and $840\text{ }\mu\text{m}$, what gives $73\text{ }\mu\text{m}$ tolerance in period design. Fig. 5a-d) present light intensity distribution for $L = 0.74\text{ }\mu\text{m}$, $L = 0.80\text{ }\mu\text{m}$, $L = 0.86\text{ }\mu\text{m}$ and $L = 0.92\text{ }\mu\text{m}$ respectively. One can notice that for larger deviations in period, interference pattern is formed in the substrate due to the interaction between zero and emerging higher order modes.

Fig. 4. Reflectivity with respect to the period L of the MHCG structure for TE polarization (solid line) and phase at the interface between GaAs substrate and MHCG (dashed line), where fillfactor F and grating thickness h_{HCG} are the optimal ones.

Fig. 5. Light intensity distribution near the MHCG surface for TE polarization, 980 nm wavelength and a) $L = 0.74 \mu\text{m}$, b) $L = 0.80 \mu\text{m}$, c) $L = 0.86 \mu\text{m}$, d) $L = 0.92 \mu\text{m}$, where fillfactor F and grating thickness h_{HCG} are the optimal ones.

In the Fig. 6 reflectivity of the MHCG with respect to the fill factor F is presented. The 99% reflectivity is sustained for fill factor between 0.311 and 0.373, what gives 0.062 tolerance in fill factor design. Fig. 7a-d) present light intensity distribution for $F = 0.2$, $F = 0.3$, $F = 0.4$ and $F = 0.5$ respectively. It is striking that even for small deviations in period, interference pattern is formed in the substrate due to the interaction between zero and emerging higher order modes and the intensity distribution is completely reorganized. Strong asymmetry is visible in the Fig. 6. On the low fill factor side, reflectivity deteriorates slowly with the fill factor change. Resulting light intensity distribution is also slowly varying. In contrary, on the high fill factor side, strong deterioration of reflectivity is observed for fill factors between 0.4 and 0.5. Resulting light intensity distribution is abruptly reorganized (Fig. 7c-d). It is worth pointing out that for standard (interleaved with low refractive index media on both sides) GaAs HCG designed for 980 nm wavelength, fill factor tolerance for 99% reflectivity is as large as 0.3 [18].

Fig. 6. Reflectivity with respect to the fill factor F of the MHCG structure for TE polarization (solid line) and phase at the interface between GaAs substrate and MHCG (dashed line), where period L and grating thickness h_{HCG} are the optimal ones.

Fig. 7. Light intensity distribution near the MHCG surface for TE polarization, 980 nm wavelength and a) $F = 0.2$, b) $F = 0.3$, c) $F = 0.4$, d) $F = 0.5$, where period L and grating thickness h_{HCG} are the optimal ones.

Fig. 8 shows reflectivity of the MHCG with respect to the MHCG thickness h_{HCG} . The 99% reflectivity is sustained for thickness between $0.158 \mu\text{m}$ and $0.170 \mu\text{m}$, what gives $0.12 \mu\text{m}$ tolerance in thickness design. Fig. 9a-d) present light intensity distribution for $h_{\text{HCG}} = 0.13 \mu\text{m}$, $h_{\text{HCG}} = 0.17 \mu\text{m}$, $h_{\text{HCG}} = 0.21 \mu\text{m}$ and $h_{\text{HCG}} = 0.25 \mu\text{m}$ respectively. Reflectivity dependence on MHCG thickness shown in Fig. 8 seems to be symmetric around optimal value of $0.164 \mu\text{m}$. What is surprising, reflectivity of zero order drops to almost 0% for $h_{\text{HCG}} = 0.067 \mu\text{m}$ and $h_{\text{HCG}} = 0.272 \mu\text{m}$. Once the thickness is increased, light intensity transforms gradually – strong interference pattern is formed in the substrate and the field intensity is increased in the MHCG gaps. Additionally, local maxima of light intensity in stripes and gaps tend to have the same z position.

Fig. 8. Reflectivity with respect to the grating thickness h_{HCG} of the MHCG structure for TE polarization (solid line) and phase at the interface between GaAs substrate and MHCG (dashed line), where period L and fill factor F are the optimal ones.

Fig. 9. Light intensity distribution near the MHCG surface for TE polarization, 980 nm wavelength and a) $h_{\text{HCG}} = 0.13 \mu\text{m}$, b) $h_{\text{HCG}} = 0.17 \mu\text{m}$, c) $h_{\text{HCG}} = 0.21 \mu\text{m}$, d) $h_{\text{HCG}} = 0.25 \mu\text{m}$, where period L and fill factor F are the optimal ones.

4. CONCLUSIONS

We have presented simulation results of monolithic high refractive index contrast grating designed for maximal reflectivity of 980 nm wavelength. Proposed design shows extraordinary optical features which, until now were distinctive for standard – cladded HCG, and reasonable manufacturing tolerances. Unique feature of this MHCG design is simplicity. Thanks to the fact that low refractive index cladding layer is no longer needed, HCG can easily be manufactured in virtually any material. This opens a way to ultra-thin, low complexity VCSELs emitting in any wavelength as far as required gain is fed to the resonator.

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