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<td>Citation</td>
<td>Gbski, M., Kuzior, O., Dems, M., Wasiak, M., Xie, Y. Y., Xu, Z. J., et al. (2014). Transverse mode control in high-contrast grating VCSELs. Optics Express, 22(17), 20954-20963.</td>
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Transverse mode control in high-contrast grating VCSELs

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Abstract: This paper presents an extensive numerical analysis of a high-contrast grating VCSEL emitting at 0.98 μm. Using a three-dimensional, fully vectorial optical model, we investigate the influence of a non-uniform grating with a broad range of geometrical parameters on the modal behavior of the VCSEL. Properly designed and optimized, the high-contrast grating confines the fundamental mode selectively in all three dimensions and discriminates all higher order modes by expelling them from its central region. This mechanism makes single mode operation possible under a broad range of currents and could potentially enhance the single-mode output power of such devices. The high-contrast grating design proposed here is the only design for a VCSEL with three-dimensional, selective, optical confinement that requires relatively simple fabrication.

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OCIS codes: (250.7260) Vertical cavity surface emitting lasers; (050.2770) Gratings; (050.6624) Subwavelength structures.

References and links


#214090 - $15.00 USD
Received 18 Jun 2014; revised 31 Jul 2014; accepted 31 Jul 2014; published 21 Aug 2014
(C) 2014 OSA 25 August 2014 | Vol. 22, No. 17 | DOI:10.1364/OE.22.020954 | OPTICS EXPRESS 20954

1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) serve as coherent optical sources and can be smoothly tuned by varying the current and temperature. An emerging application for such devices is in portable gas sensors based on tunable diode laser spectroscopy. Multimode operation is acceptable for short-distance optical data transmission. However, efficient lateral optical confinement is crucial in order to minimize the threshold current and maximize the modulation speed. VCSELs inherently emit in single longitudinal mode thanks to their very short cavities which are sandwiched between two distributed Bragg reflectors (DBR) and control the mode in the vertical direction. Controlling the modes in the transversal direction is far more complicated. In typical VCSELs made from arsenide-based materials, this can be achieved using well-established wet oxidation technology [1]. In shorter- and longer-wavelength VCSELs, other methods of transverse mode confinement may be used which provide higher threshold currents but can require more expensive technology. The most common approach is to use micro-optical structures: surface relief [2], anti-resonant patterning [3], tunnel junction patterning [4] and photonic crystals [5].

Sub-wavelength high-contrast gratings (HCGs) offer new possibilities for three dimensional mode confinement through a single structure localized on top of the device. Properly chosen grating parameters can ensure that zero and first diffraction orders exist in the grating layer [6]. Coupling between an incident wave and the grating modes at the input and output interfaces results in an asymmetric Fano resonance [7], providing almost 100% reflectivity. This high reflectivity is a consequence of the destructive interference between the transmitted zero order grating mode and the first order mode at the output interface of the grating.

Since the propagation of the grating mode depends on the grating parameters, these parameters can also be adjusted to prohibit the propagation of light in the plane of an HCG. Figure 1(a) shows the HCG that we discuss here, which consists of a central part which supports the propagation of the grating mode and two outer parts which prohibit propagation by confining the light in the transverse direction (along the x axis) while the whole structure confines it in the vertical direction (along the z axis) [8]. The third confining mechanism (along the y axis) is the waveguiding effect, since the HCG is composed of materials with a higher effective refractive index than the surroundings. Since the HCG modifies the modal...
properties, it is possible to achieve lasers which differ in wavelength, mode discrimination, mirror reflectivity and emitted power etc. on one wafer. Unlike selective oxidation, which is difficult to be controlled and examined as it is located inside the cavity, the quality of the fabricated HCG can be easily controlled by nondestructive microscopic methods e.g. using a scanning electron microscope [9]. A serious additional drawback of the selective oxidation is the significant degradation which reduces the lifetime of lasers [10].

HCGs can therefore be a very appealing alternative to the DBRs generally used in VCSELs [9], since they provide a reflection spectrum that is almost twice as broad [11], ensure extremely sharp polarization discrimination [12], reduce the dimensions of the laser, and lower manufacturing costs. HCGs can be 20-30 times thinner than DBRs and may be used in arsenide, silicon, nitride and phosphide alloys [13–16]. The most straightforward utilization of an HCG is as the top mirror of a VCSEL [17]. Suspended HCG membranes have been previously investigated in nanoelectromechanical optoelectronic tunable VCSELs, where they were shown to enable broad and extremely fast tuning [18–20]. Because of the above mentioned advantages of HCGs, further investigations are continued to be required, for instance, to achieve transverse mode control for single transverse mode operation.

In this paper, we aim to provide an extensive numerical analysis of high-contrast grating VCSEL, through the use of a three-dimensional fully vectorial optical model, to investigate the influence of a non-uniform grating with a broad range of geometrical parameters on the modal behavior of the VCSEL. Based on the analysis, it is found that properly optimized high-contrast grating makes single mode operation possible under a broad range of currents.

2. Structure and numerical model

Our study is based on a two-layer HCG structure positioned on top of a 980 nm VCSEL, as described in Table 1 (see also Fig. 1(a)). A 1λ-thick optical cavity is sandwiched between the bottom DBR and the top HCG. The HCG comprises a low refractive index layer (cladding), composed of AlOx with a thickness of \( h_{\text{clad}} \) and refractive index \( n_{\text{clad}} = 1.55 \) and high refractive index GaAs stripes of thickness \( h_{\text{HCG}} \) and refractive index \( n_{\text{HCG}} = 3.52 \). In the grating layer, we defined three regions with different fill factors \( F \) which is defined as the ratio of the stripe width to the HCG period \( L \) (see Fig. 1(b))

![Fig. 1. Schematics of the VCSEL structure a) and an HCG b) together with the coordinate system, where \( L \) - the HCG period, \( LF \) - width of the HCG stripes, \( h_{\text{HCG}} \) - thickness of the HCG stripes, \( h_{\text{clad}} \) - thickness of the cladding](image)
Table 1. Layer thicknesses and refractive indices of a 980 nm HCG VCSEL. The top three layers (HCG stripes, HCG cladding and upper VCSEL Spacer) are used in the HCG simulations.

<table>
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<th>Layer</th>
<th>Refractive index</th>
<th>Layer thickness [μm]</th>
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<tr>
<td>Air</td>
<td>1</td>
<td>∞</td>
</tr>
<tr>
<td>HCG stripes</td>
<td>3.52</td>
<td>0.103</td>
</tr>
<tr>
<td>HCG cladding</td>
<td>1.55</td>
<td>0.417</td>
</tr>
<tr>
<td>VCSEL cavity</td>
<td>3.52</td>
<td>0.2783</td>
</tr>
<tr>
<td>35 DBR pairs</td>
<td>2.95</td>
<td>0.0830</td>
</tr>
<tr>
<td>Substrate</td>
<td>3.52</td>
<td>∞</td>
</tr>
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Using the 3D fully-vectorial Plane Wave Admittance Method [21], we investigated the influence of the geometry of the HCG structure on the fundamental mode distribution, the wavelength of the emitted light and the $Q$-factor of a GaAs-based VCSEL, which is defined as follows [22]:

$$Q = \frac{\text{Re}(k_0)}{2\text{Im}(k_0)}$$

where $k_0$ is the free space wave vector.

Our model combines two very effective approaches. In the plane of the epitaxial layers, the field is expanded on the basis of exponential functions and, using the Admittance Method, is transformed through the layers determining an eigenvalue problem, which gives as a solution the effective wavelength of the mode and the distribution of the mode within the structure [21].

3. Uniform HCG

The reflectance of the HCG is strongly dependent on the thickness of the HCG cladding (Fig. 2(a)). In the case of the HCG design considered here, the reflectivity changes periodically with the cladding thickness [23]. The periodicity is related to the reflections that appear at the interface between the substrate and the cladding and, on the opposite interface, between the cladding and the HCG. The period of the oscillations is 0.316 μm [23], which corresponds to half of the wavelength in the oxide layer. The maximal reflectance appears in thickness periods of the oxide layer equal to $0.5 m \lambda/h_{\text{clad}}$ where $\lambda$ is the vacuum wavelength and $m$ an arbitrary integer number.

In order not to exceed the critical thickness of the oxide layer, we chose to base further calculations on an $h_{\text{clad}} = 417$ nm. The thickness of the cladding layer affects not only the reflectance but also the wavelength shift with temperature $\frac{d\lambda}{dT}$. Figure 2(b) shows that $h_{\text{clad}} = 417$ nm relates to the maximum of $\frac{d\lambda}{dT}$ and structures of thicker cladding ($h_{\text{clad}} = 550$ nm) can be expected to be less thermally sensitive.
Fig. 2. HCG reflectance a) and thermal wavelength shift of an HCG VCSEL b) as a function of the oxide thickness ($h_{\text{clad}}$).

Figure 3(a) shows the reflectance map in the domain of $F$ and $L$. The two other parameters, cladding thickness and the thickness of the HCG stripes, have been set to their optimal values which are $h_{\text{clad}} = 417$ nm and $h_{\text{HCG}} = 103$ nm [23]. The white dot in Fig. 3(a) is located in the broad region of very high reflectivity, and corresponds to parameters which do not produce the maximal reflectivity, but which minimize the manufacturing error. These parameters produce a reflectance greater than 99.9% in the case of the infinite mirror. Covering the VCSEL cavity with a finite HCG mirror using the same parameters produces three-dimensional confinement. The lowest four order modes confined within the area of the HCG are depicted in Fig. 3(b). We call HE$_{11}$ and HE$_{21\perp}$ 'perpendicular' since the distributions of their lobes are perpendicular to the stripes, while HE$_{21\parallel}$ and HE$_{22}$ are parallel to the stripes. The grating mode ($x$ component of the wave vector) propagates perpendicularly to the stripes in the plane of the HCG and therefore leaks laterally – an effect that is particularly noticeable in the case of the HE$_{21\parallel}$ and HE$_{22}$ modes, which consist of two lobes along the $x$ axis. The difference in leakage affects the quality factors ($Q$-factors) of the modes. The $Q$-factors of HE$_{11}$ and HE$_{21\perp}$ are relatively close and significantly larger than the $Q$-factors of HE$_{21\parallel}$ and HE$_{22}$, respectively, since both modes are weakly confined within the area of the HCG (Fig. 3(b)).

Transverse leakage perpendicularly to the HCG stripes can be reduced by reflecting the HCG mode at the borders of the HCG. In what follows, we show that transverse confinement can be enhanced by tuning the HCG parameters.
4. Nonuniform HCG

To investigate the transverse confinement induced by the outer stripes with different fill factors, we consider a three-region HCG (Fig. 4). The central part consists of 12 stripes with optimized parameters (Fig. 3(a)), while two identical outer parts are comprised of 4 stripes of the same period \(L\) as in the central part but with different fill factors \(0.25 < F_{bar} < 0.5\), which still sustain reflectance of over 99% (Fig. 3(a)).

![Fig. 4. Top view of a three section HCG with defined parameters.](image)

Figures 5(a) and (b) show the evolution of the HE\(_{11}\) mode induced by changing the \(F_{bar}\). Starting with a uniform HCG \(F_{bar} = F_{ap} = 0.4\) and increasing \(F_{bar}\) the transverse distribution of the mode shrinks and reduces transverse leakage. Beginning again with \(F_{bar} = F_{ap} = 0.4\) and decreasing the \(F_{bar}\) the leakage initially increases \((F_{bar} = 0.38)\), while further decreasing the \(F_{bar}\) reinforces the transverse confinement of the mode and reduces the leakage.

The modifications of the transverse leakage of HE\(_{11}\) mode observed find their confirmation in the calculated dependence of the \(Q\)-factor relative to \(F_{bar}\) (Fig. 6). The \(Q\)-factor of the HE\(_{11}\) mode is minimal at \(F_{bar} = 0.38\) and reaches the maximum at equidistant

![Fig. 5. Intensity distributions of the HE\(_{11}\) in the plane of the active region a) HE\(_{11}\) in the plane perpendicular to epitaxial layers b) and HE\(_{21}\) in the plane of the active region c) for \(F_{ap} = 0.4\).](image)
points $F_{\text{bar}} = 0.28$ and $F_{\text{bar}} = 0.48$ suggesting periodic behaviour. The maximum at $F_{\text{bar}} = 0.28$ is somewhat larger than at $F_{\text{bar}} = 0.38$, which is related to the thinner HCG barrier stripes which enhance the waveguide mechanism. Since the $x$-direction distribution of HE$_{21\perp}$ is very close to that of HE$_{11}$ the $Q$-factors of both modes are also very similar. The difference in $Q$-factors originates from the mode distribution along the stripes ($y$-direction). The dominant influence which increases the $Q$-factor is the intensification of optical confinement along the $x$ axis, but this effect also forces stronger leakage along the $y$ axis as a secondary effect, somewhat lowering the $Q$-factor. Since the two-lobe distribution of HE$_{21\perp}$ is wider than that of HE$_{11}$, HE$_{21\perp}$ suffers stronger leakage and the reduction of its $Q$-factor is greater due to this secondary effect. The strongest confinement in the $x$-direction produces the most intense leakage in the $y$-direction, hence at the maximum of $Q$-factors ($F_{\text{bar}} = 0.28$ and $F_{\text{bar}} = 0.48$) the discrimination between the modes HE$_{11}$ and HE$_{21\perp}$ is also the greatest. The other modes, with multiple lobes along the $x$ axis (HE$_{21\parallel}$ and HE$_{22}$), are strongly discriminated. They move from the central part of the HCG towards the barriers, and suffer strong leakage (Fig. 5(c)). This effect is more pronounced in the case of larger $F_{\text{bar}}$, since the barriers have a higher effective index than the central part. The lobes of HE$_{21\parallel}$ and HE$_{22}$ tend therefore to migrate to the barriers.

4.1 Influence of the aperture

An additional method of discriminating the mode HE$_{21\perp}$ is to reduce of the length of the HCG stripes, which reduces the size of the optical aperture. In this study, we are considering an HCG consisting of barriers with four stripes, which limit the square-like aperture (Fig. 7). The size of the aperture is determined by the number of central stripes ($n_a$), which in our calculations varies from 2 to 20.

Figure 8 illustrates the $Q$-factor of four of the lowest order modes as the function of the number of central stripes. In the case of smaller apertures ($n_a < 8$), the $Q$-factor of the
fundamental mode is significantly larger than those of the others. Increasing the size of the aperture increases the $Q$-factors and reduces the discrimination between HE$_{11}$ and HE$_{21\perp}$. The behaviour of the 'parallel' modes differs due to their different $F_{\text{bar}}$. In the case of $F_{\text{bar}} = 0.28$

![Graph](image)

Fig. 8. $Q$-factor of four the lowest order modes as a function of the number of HCG stripes in the aperture for $F_{\text{bar}} = 0.28$ a) and $F_{\text{bar}} = 0.48$ b)

the effective index of the central part of the HCG is larger than that of the barriers. This mechanism confines all the modes, and the $Q$-factors of the modes are closer than when $F_{\text{bar}} = 0.48$. In this case, the effective index is larger in the barriers, which means that the 'parallel' modes are expelled from the central part of HCG and locate their lobes in the barriers. This analysis reveals that barriers play an important role in mode filtering.

4.2 Influence of the barriers

In the previous section, we have discussed the influence of barriers on mode filtering. This final section concerns the influence of barrier size on mode discrimination. The same HCG design is considered as in section IV, but the variable parameter is the number of stripes in the barrier ($n_b$). Figure 9 provides a schematic view of these HCG designs.

![Diagram](image)

Fig. 9. The top view of several HCG configurations with different numbers of HCG stripes in the barriers ($0 \leq n_b \leq 9$) and a constant number of stripes in the aperture ($n_a = 12$).

Figure 10 illustrates the dependence of the $Q$-factor of the four lowest order modes on the number of stripes in the barriers. In both cases ($F_{\text{bar}} = 0.28$ and $F_{\text{bar}} = 0.48$), increasing the $n_b$ will increase not only the discrimination of the 'parallel' modes, but also the difference between HE$_{11}$ and HE$_{21\perp}$. In the case of $F_{\text{bar}} = 0.28$ (Fig. 10(a)), the evolution of the $Q$-factors is not monotonic, due to the significant modification of the transverse distributions of the modes (the evolution of the mode HE$_{11}$ is presented in Fig. 11(a) as an example).
An increase in barrier size leads to the barriers being penetrated by the mode. When $n_b > 6$ the mode is expelled from the central region. The lobe splits and locates in the barriers. This mode migration is induced by the standing wave formation in the transverse direction, which tends to locate in the regions of lower refractive index [24]. When $F_{\text{bar}} = 0.48$ (Fig. 10(b)), the increases in $Q$-factor of all the modes are almost linear and HE$_{11}$ is dominant not only over the ‘parallel’ modes but also over HE$_{21\perp}$. Figure 11(b) illustrates the evolution of the HE$_{11}$ mode with different numbers of stripes in the barriers. When $n_b > 6$ the mode converts to the shape with two lobes which tend to migrate to the barriers. Unlike the case when $F_{\text{bar}} = 0.28$, this migration is induced by the waveguide effect, since barriers have a larger fill factor with respect to the central region. The dashed lines show the $Q$-factor of all modes when the fill factor of the barriers is equal to that of the central region. This comparison proves that a carefully designed three-section HCG can provide a high $Q$ VCSEL cavity, which is impossible with uniform HCGs (see Fig. 6 for $F_{\text{ap}} = 0.4$).
5. Conclusion

This paper presents the results of an extensive numerical analysis of the optical transverse and horizontal confinement produced by a three section high-contrast grating incorporated as the top mirror of a 980 nm VCSEL. Using a three-dimensional vectorial optical model, we investigated the influence of a three-section HCG with a broad range of geometrical parameters on the Q-factors of the VCSEL modes. The confinement of the mode can be ensured by preventing light propagation in the plane of the HCG by tuning the HCG parameters. We analysed an HCG structure divided into three parts, the central part playing the role of the aperture and the transverse regions acting as a barrier to the HCG mode. The parameters of the central region were chosen so as to achieve maximal reflectance. The fill factor of the HCG was assumed to be $F_{\text{app}} = 0.4$ and the strongest mode confinement was produced when the fill factors of the barriers were $F_{\text{bar}} = 0.28$ and $F_{\text{bar}} = 0.48$.

Strong discrimination was found to occur when the size of the central region was less than 10 stripes. Discrimination can be enhanced further, even in the case of a larger aperture ($n_a = 12$), if the number of stripes in the barriers is chosen carefully ($n_b = 5$). Having more than 5 HCG stripes in the barriers pushes the modes out of the central region, which in turn reduces the efficiency of the laser.

This study shows that nonuniform HCGs can provide efficient and selective confinement of the transversal modes. The benefits of this approach include not only the promise of extraordinary optical properties, but also the design proposed here requires relatively simple fabrication, opening the way for the use of HCGs in various kinds of material systems.

Acknowledgments

This work is jointly supported by the Polish National Centre of Research and Development and by Singapore A*STAR (grant no. 122 070 3063) in the framework of the project: ‘A Novel Photonic Crystal Surface Emitting Laser Incorporating a High-Index-Contrast Grating’. M. Dems acknowledges the support of the Polish National Center for Research and Development within the project LIDER.