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# Comparison between high- and zero-contrast gratings as VCSEL mirrors

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## ABSTRACT

This study presents a comparison between high-contrast gratings (HCGs) and zero-contrast gratings (ZCGs) for high-speed vertical-cavity surface-emitting lasers (VCSELs). Both types of gratings exhibit high reflectivities beyond 99.5% due to the destructive interference at the output plane, but the HCG has a broader high reflectivity band. The HCG has a lower reflection delay time and smaller energy penetration length than the ZCG. The HCG has poorer mode selectivity for the VCSEL than the ZCG. The fabrication of the ZCG is less complex but with tight fabrication tolerances.

## 1. Introduction

High-speed, energy-efficient, and temperature-stable vertical-cavity surface-emitting lasers (VCSELs) have been attracting enormous attention because they are the ideal sources for optical interconnects in data centers and high-performance computers [1–7]. In 2015 a 71-Gb/s 850-nm VCSEL based optical link with advanced driver and receiver chips incorporating two tap feed forward equalization at room temperature was demonstrated [8]. Record energy efficiency of 56 fJ/bit, 46 Gb/s data rate, and a 23-GHz modulation bandwidth at 85 degrees were reported for VCSELs at 850 or 980 nm [9,10]. These exciting results are achieved by the adoption of a short cavity, optimization of the photon lifetime, advanced active layer design, optimized device structure, and advanced driver. Even though higher-order modulation formats, advanced driver chips, and superior photoreceiver systems will be beneficial to achieve still lager data rates [9,11], improving the performance of the VCSEL itself is essential. Novel nanoscale surface structures like high contrast gratings (HCGs) are expected to pave the way for further improvement because of their unique properties [12].

HCGs are subwavelength gratings with grating bars fully surrounded by a low-index medium like air. One typical application of HCGs is for wide-band and high-reflectivity reflectors to replace part of the top distributed Bragg reflector (DBR) of VCSELs [13–18]. Ref. [12] pointed out, that the high reflectivity of the HCG is due to destructive interference at the output plane. The broadband reflectivity of the HCG is supposed to be a result of the large index contrast between the HCG bars and the surrounding. Recently Magnusson [19] designed a zero-contrast grating (ZCG) for a broadband reflector and concluded that a high index contrast is sufficient but not necessary for broadband reflectors. The ZCG reported in [19] is a surface relief grating sitting on the low-index substrate and the wave is incident from the air side. A grating structure similar to the ZCG was reported but without a low-index substrate and the wave is incident from the homogenous semiconductor material side [20–23].

One of the important applications of HCGs is serving as reflectors of VCSELs [13]. In the fabrication of HCG-VCSELs, a sacrificial layer below the HCG layer is always removed to create a suspended HCG. Therefore a lattice matched material system is very critical from the perspective of both device performance and fabrication feasibility. The current HCG-VCSELs fabrication is based on the complicated and expensive critical point drying process for grating release. Here the ZCGs are used to replace the total or part of the top DBR of the VCSELs. The sacrificial layer removal step in the HCG fabrication is not required for the ZCG fabrication. The whole device fabrication is highly simplified and the mechanical stability is improved. In this work, HCGs and ZCGs will be designed and compared with respect to the reflectivity, reflection phase, mode selectivity, size effect, and fabrication tolerance for high-speed VCSEL applications.

## 2. Simulations and results

### 2.1. Simulation models

The target wavelength for HCGs and ZCGs is 980 nm, which is a very popular wavelength for optical interconnects in Datacom and

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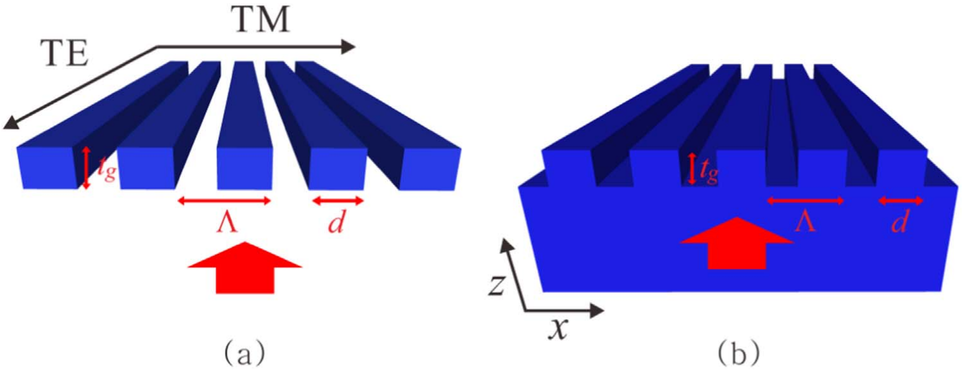

**Fig. 1.** Schematics of HCGs (a) and ZCGs (b). The grating period is Λ, and $d$ is the width of the grating bar. The duty cycle (DC) is defined as $d/\Lambda$, and $t_g$ is the thickness of the grating. The surrounding of HCG bars is air. The red arrows represent the incident light. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Computercom. GaAs (refractive index $n$=3.526) can be used for the grating, because it is transparent and is assumed to be lossless and dispersion free in the calculations for the concerned wavelength range. The schematics of the calculation model for HCGs and ZCGs are shown in Fig. 1. The grating period is Λ, $d$ is the width of the grating bar, the duty cycle (DC) is defined as $d/\Lambda$, and $t_g$ is the thickness of the grating. The transversal magnetic (TM, the electric component is perpendicular to the grating bars) polarization is considered because the evanescent tail through the output plane is shorter than the transversal electric (TE, the electric component is parallel to the grating bars) polarization [15]. However, the gratings for TE polarization can be also designed with the same method. For VCSELs, the incident wave is from the active region inside the semiconductor towards the grating/air interface. Rigorous coupled wave analysis (RCWA) and 2-dimensional finite-difference time-domain (2D-FDTD) methods are used to calculate the reflectivity spectra and the field distributions, as reported in [24,25].

### 2.2. Reflectivity

The reflectivity maps for HCGs and ZCGs are calculated by RCWA method and shown in Fig. 2 for the normalized wavelength (λ/Λ) and the normalized thickness ($t_g/\Lambda$) of the grating. One high reflectivity region in the reflectivity map of the HCG has an *S*-shape and provides a wide range of thickness $t_g$ for obtaining high reflectivity across a broad band. The reflectivity map of the ZCGs is very different from the HCGs. The range of $t_g$ for high reflectivity at a given wavelength is very small and the wavelength range for high reflectivity is narrower than for HCGs. That means, the reflectivity of the ZCG is very sensitive to $t_g$, which will be further discussed in Subsection 2.7.

According to Fig. 2, for the HCG we set Λ to 415 nm, and $t_g$ to 292 nm. To maximize the reflectivity and band, DC is scanned and set to 0.51. The parameters of the ZCG are Λ=450 nm, and $t_g$=304 nm. Then DC is also scanned and set to 0.51. The following comparisons will be based on the HCG and ZCG with the previous parameters (HCG, Λ=415 nm, $t_g$=292 nm, DC=0.51; ZCG, Λ=450 nm, $t_g$=304 nm, DC=0.51). The reflectivity spectra for infinite-size gratings are shown in Fig. 3. The shapes of the two curves for HCG and ZCG are similar. The HCG shows a reflectivity of $>99.5\%$ from 932 to 1031 nm, resulting in a bandwidth of 99 nm. The ZCG has a 41-nm bandwidth, from 966 to 1007 nm for the reflectivity $>99.5\%$. At a wavelength of 980 nm the reflectivity can be as large as 99.9%, which is sufficient for VCSELs. Thus the ZCG has a narrower band width ($\Delta\lambda/\lambda_O$=4.2%, $\Delta\lambda$ is the wavelength range with reflectivity higher than 99.5%, $\lambda_O$ is 980 nm) than the HCG ($\Delta\lambda/\lambda_O$=10.1%). It should be noted that for incident waves from the air side of the ZCG, the reflectivity spectrum is very different from the one from the GaAs side, due to the spatial symmetry breaking.

The steady-state field distributions ($H_y$ component) in one unit cell of a HCG and a ZCG at 980 nm are calculated by FDTD method and shown in Fig. 4(a) and (c), respectively. It should be noted that the steady-state field distributions can be reproduced by RCWA method. The field distributions at the grating regions are almost the same. The field is almost completely localized at the centers of both the grating

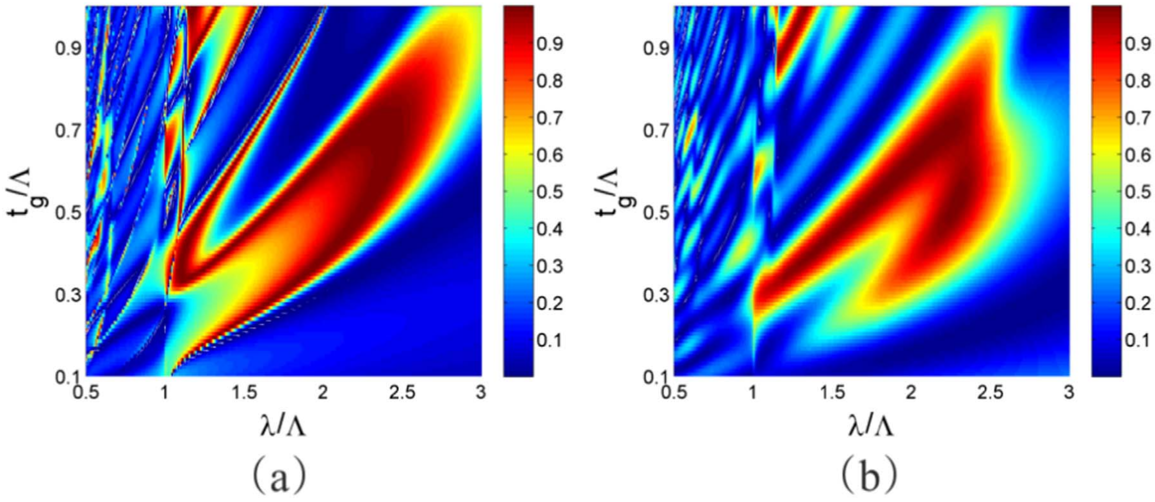

**Fig. 2.** Reflectivity maps of HCG (a) and ZCG (b) for the TM polarization for DC=0.5 by RCWA method. The color bars show the reflectivity, where red is the highest. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)