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Polarization-independent high-index contrast grating and its fabrication tolerances

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A polarization-independent, high-index contrast grating (HCG) with a single layer of cross stripes allowing simple fabrication is proposed. Since the cross stripes structure can be suspended in air by selectively wet-etching the layer below, all the layers can be grown at once when implemented for vertical-cavity surface-emitting lasers. We optimized the structure to have a broad and high reflectivity band centered at around 1 \(\mu\)m using a finite difference time domain method, and obtained an 80 nm high reflectivity band centered at 0.97 \(\mu\)m in which the reflectivity exceeded 99.5%. We also investigated the fabrication tolerances of the structure and found that, assuming careful optimizations of electron beam lithography for the precise grating width and dry-etching for the vertical sidewall, the suggested polarization-independent HCG can be fabricated using standard technologies. © 2013 Optical Society of America


1. Introduction
Recently, high-index contrast gratings (HCGs) featuring broadband reflectivity and being much thinner than conventional distributed Bragg reflectors (DBRs) have been proposed [1] and vertical-cavity surface-emitting lasers (VCSELs) exploiting the HCG have been demonstrated [2,3]. The HCG reflectors work based on guided mode resonance (GMR) under the phase-matching condition with the second-order grating [4,5]. When it is used for a broadband reflector instead of a DBR in VCSELs, the effective cavity length can be significantly reduced [6], which could contribute to faster modulation. Specifically, we expect faster polarization switching in the case of polarization-bistable VCSELs [7] due to the faster cavity buildup time for lasing. To apply HCGs to polarization-bistable VCSELs, the reflectivity has to be polarization independent. Although polarization-independent HCGs have been proposed [8–10], these structures are not suitable for VCSELs because of the complexity in fabrication. The two-dimensional (2D) periodic islands structure [8,9] requires a low-index supporting material such as SiO\(_2\) under the grating, which needs film depositions additional to the crystal growth. The cross-stacked grating [10] apparently requires more process steps to fabricate. In this paper, we propose a single layer cross-striped HCG which can be fabricated more easily using the air-bridge structure [2,3] and can provide processing robustness for large-area HCGs, preventing grating lines from sticking to each other. We numerically investigate the structure for a polarization-independent broadband reflectivity and also the fabrication tolerances of an optimized structure.

2. Polarization-Independent HCG
Figure 1 shows our HCG structure, which consists of a semiconductor 2D grating, a low refractive index layer, and a semiconductor substrate. The
cross-striped structure can be suspended in air by selectively wet-etching the underlayer as opposed to the 2D periodic islands structure. Therefore, all the layers for a HCG–VCSEL can be grown at once \[ W/T \] and \[ n \] to keep the reflectivity higher than 99.5% at a wavelength of 0.97 \( \mu m \) and those split bands have a quite narrow bandwidth. It is thus found from Fig. 3(a) that the fabrication tolerance for \( W \) will be about \( \pm 10 \) nm to keep the reflectivity higher than 99.5% at a wavelength of 0.97 \( \mu m \). Electron beam lithography has this level of pattern definition accuracy under carefully controlled conditions [14]. Optical lithography may also achieve such pattern definition accuracy [15]. We also calculated the case with nonvertical sidewalls as presented in Fig. 3(b). The definition of the

![Fig. 1](image1.png)

**Fig. 1.** Polarization-independent HCG with a single layer of cross stripes for simple fabrication.

![Fig. 2](image2.png)

**Fig. 2.** (Color online) (a) Calculated power reflectivity spectrum of the optimized HCG (\( \Lambda = 556 \) nm, \( W = 178 \) nm, \( T_g = 270 \) nm, \( T_L = 630 \) nm, \( n_g = 3.5, n_L = 1 \)). (b) The electric field distribution (linear polarization perpendicular to the paper) in the unit cell for a wavelength within the high-reflectivity band.
A tilted angle $\theta$ is described in the inset of Fig. 3(b). We observe that the high reflectivity band splits into two when $\theta$ is larger than $\pm 8^\circ$. It is thus found from Fig. 3(b) that the fabrication tolerance for $\theta$ will be about $\pm 6^\circ$. This level of vertical dry-etching is also possible under carefully controlled conditions $[16]$. Similar considerations for the other structural parameters resulted in $T_g = 270 \pm 30$ nm, $T_L = 630 \pm 130$ nm, and $n_g = 3.5 \pm 0.1$, respectively, as shown in Figs. 3(c)–3(e). Since we assume that the grating and low index layers are all grown with molecular beam epitaxy (MBE), the above tolerances of $T_g$ and $T_L$ are not critical. It is worth noting that if the MBE growth has a $\pm 10$ nm thickness error, different choices of $T_g$ and $T_L$ will be possible. For example, $T_g = 250$ nm results in a wider bandwidth of $\sim 100$ nm as seen in Fig. 3(c), and $T_L = 510$ nm provides a shorter effective cavity length although the bandwidth becomes slightly narrower, as seen in Fig. 3(d). Finally, the above tolerance of $n_g$ is not critical either since the composition of the grating material (e.g., Al$_x$Ga$_{1-x}$As) can be well controlled by MBE.

It is interesting to consider the effect of an asymmetric fabrication error on the polarization-independent reflectivity. Our structure is polarization independent because of the $90^\circ$ rotational symmetry. However, an asymmetric fabrication error, for example, $W_x = 178 + 5$ nm, $W_y = 178 - 5$ nm, results in a polarization-dependent reflectivity as shown in Fig. 4. We see that the high reflectivity bands for $E_x$ and $E_y$ linear polarizations shift in the same manner as in Fig. 3(a), but have an overlap of between 0.95 and 1 $\mu$m, where the polarization-independent property almost holds. When applied to VCSELs, the maximum reflectivity difference at 0.98 $\mu$m, i.e.,
$R_{\text{HCG}} \approx 0.997$ and $\sim 0.999$ for $E_\parallel$ and $E_\perp$ polarizations, respectively, results in an 8% difference of lasing threshold gains $g_{\text{th}}$, assuming a simple relation of $g_{\text{th}} = a + 1/(2d) \cdot \ln(1/\sqrt{R_{\text{HCG}} - R_{\text{DBR}}})$ with a loss inside the cavity of $a = 20 \text{ cm}^{-1}$, a reflectivity of the opposing DBR mirror of $R_{\text{DBR}} = 0.999$, and a cavity length of $d = 3 \mu\text{m}$ [17]. Further optimization to minimize the dent in the high-reflectivity band will be possible for more robust polarization independence.

Finally, we investigate the effect of absorption in the grating material on the reflectivity. We assume that the absorption originates from carriers unintentionally ($p$-type at $2 \times 10^{14} \text{ cm}^{-3}$) or intentionally ($p$-type at $2 \times 10^{16} \text{ cm}^{-3}$) doped in MBE growth. The absorption coefficients at the doping levels above are calculated as $a = 0.4$ and $29.3 \text{ cm}^{-1}$, respectively, using the corresponding mobilities in Al$_{0.6}$Ga$_{0.4}$As [18], which is a typical material used in air-bridge HCG–VCSELs [2,3]. The power reflectivity spectra calculated using the absorption coefficients are plotted in Fig. 5. We see that the carrier density intrinsically included in MBE-grown crystals ($\sim 2 \times 10^{14} \text{ cm}^{-3}$) does not change the reflectivity spectrum, while the carrier density intentionally doped ($2 \times 10^{16} \text{ cm}^{-3}$) reduces the reflectivity.

From the inset of Fig. 5, a carrier density higher than $2 \times 10^{16} \text{ cm}^{-3}$ will result in a reflectivity lower than 99.5% which makes an impact on the lasing threshold gain in HCG–VCSELs.

4. Conclusions

We have proposed a polarization-independent HCG with a single layer of cross stripes for simple fabrication. An 80 nm high-reflectivity band centered at a wavelength of 0.97 $\mu\text{m}$, in which the reflectivity exceeds 99.5%, was obtained using optimized structural parameters. The bandwidth is similar to that realized by DBR mirrors and the reflectivity achieved is sufficient for VCSELs. We have also investigated the fabrication tolerances of the structure and found that, assuming careful optimizations of electron beam lithography for the $W$ tolerance of $\pm 10 \text{ nm}$ and dry-etching for the $\theta$ tolerance of $\pm 6^\circ$, the polarization-independent HCG can be fabricated using standard technologies. In addition, it has been found that material absorption originating from carriers intrinsically included in MBE-grown crystals ($\sim 2 \times 10^{14} \text{ cm}^{-3}$) does not reduce the reflectivity, while a carrier density higher than $2 \times 10^{16} \text{ cm}^{-3}$ will result in a reflectivity lower than 99.5%, which makes an impact on the lasing threshold gain in HCG–VCSELs.

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