Waveguide grating mirror for large-area semiconductor lasers

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Received February 13, 2001

We have fabricated and tested a waveguide grating mirror that uses anomalous reflection of light associated with excitation of waveguide modes. Sharp features are observed in the reflection spectra in both the wavelength and the angular domains. We confirm experimentally that, when the waveguide grating mirror is placed a short distance in front of a large-area semiconductor laser, it can control the emission spectrum. This demonstration opens a new approach to the design of very compact semiconductor lasers operating in the single-frequency–single-mode regime. © 2001 Optical Society of America

OCIS codes: 050.0050, 050.1950, 140.0140, 140.3410.

Light reflection from a surface of a periodically corrugated planar waveguide reveals sharp features similar to Wood anomalies of metal gratings.1 In contrast with a metal surface, a dielectric waveguide can maintain modes of both TE and TM polarization, so the anomalies exist for any polarization of input light. Anomalous reflection in the case of a lossless waveguide can approach 100% close to resonant waveguide excitation, whereas far from the resonance the reflection is small (e.g., ~4% for glass-based weakly guiding structures). Thus anomalous reflection can potentially be used in narrow-band optical filters (see, e.g., Refs. 2–5). To the best of our knowledge, the narrowest anomalous reflection peak was observed in the study reported in Ref. 6 (FWHM 0.12 nm in the 1.55-μm wavelength region; maximal reflection 56%). Off-resonant reflection is a major technical difficulty in the practical application of such filters. To a certain degree the problem can be solved by application of antireflectance coatings on top of the waveguide layer or by use of the Brewster’s angle geometry, but it is hardly possible to get strong suppression of the off-resonant reflection over a wide range of incident angles and wavelengths (e.g., communication applications require from ~20- to ~30-dB suppression over a 1530–1620-nm wavelength range).

Another application of anomalous reflection is emission-spectrum and transverse-mode control in lasers. Because of the threshold nature of laser generation, off-resonant reflection is no longer a problem. A bulk scheme for a dye laser with a waveguide grating mirror operating at visible wavelength was demonstrated in Ref. 7. A similar scheme with near-infrared dye was reported in Ref. 8. On a smaller scale, a waveguide grating mirror and proper collimating optics were demonstrated to provide single-frequency operation of a single-mode Fabry–Perot semiconductor laser.5 In microchip solid-state lasers, anomalous reflection was shown to control the output polarization.9

Also, numerous diverse filters have been used to control a semiconductor laser’s spectral and spatial modes. None of the approaches used is so simple, compact, and potentially robust and reliable as one based on the concept of the waveguide grating mirror. In this Letter we report an experimental study of a large-area semiconductor laser with a waveguide grating mirror installed at the front facet of the laser.

The physical nature of spatial filtering in a laser resonator with a waveguide grating mirror consists of widening of a reflected beam owing to waveguide modes propagating beyond the spot illuminated by an incident beam.10 To a certain degree this mechanism is similar to suppression of filamentation in lasers with unstable resonators by use of convex mirrors (see, e.g., Ref. 11). There is, however, a substantial difference. In unstable resonators the beam width increases geometrically with the number of reflections, whereas in a resonator with a waveguide grating, beam widening is approximately proportional to the number of reflections. The spatial filtering scheme discussed in this Letter is rather close in its physical mechanism to that of an angled-grating distributed-feedback laser.12 Therefore we expect that perfectly optimized structure will eventually provide laser radiation quality similar to angled-grating lasers. The advantage of a waveguide grating mirror over an angled grating is basically technological: It does not require regrowth, so the technology is potentially more robust, more reliable, and less expensive.

To fabricate the waveguide grating mirror (Fig. 1) we used TiO$_2$–SiO$_2$ sol-gel planar waveguides on glass substrate, which are commercially available for biosensing applications. The waveguides were carefully characterized by use of a prism coupler and a computer-controlled rotation stage with resolution of 1 arc sec. Then we fabricated holographic gratings in a layer of deep-UV photore sist (JSR-KRF-TMX1113Y, JSR Microelectronics),

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Fig. 1. Schematic view of the waveguide grating mirror.
using the second harmonic of an Ar$^+$-ion laser (257 nm). This particular photore sist has very small optical absorption in the visible and near-infrared region, so we were able to observe sharp reflection resonances with a photore sist grating, although real applications will definitely require dry etching and removal of residual resist. We adjusted the grating period and the photore sist thickness to provide a normal-incidence anomalous reflection peak at the operation wavelength of the large-area semiconductor laser.

Angular reflection spectra at different wavelengths, measured with a Ti:sapphire tunable laser, are shown in Fig. 2. Reflection from the backside of the substrate was decreased by use of index-matching oil and a glass prism attached to the sample. The measured spectra show sharp peaks in both the wavelength and the angular domains. Except for a narrow-wavelength region near $\lambda = 794$–795 nm, each angular spectrum has two sharp peaks associated with excitation of waveguide modes propagating in opposite directions. When excitation of both modes happens simultaneously at normal incidence, the reflection peak becomes a bit wider and stronger in magnitude. Maximal reflectance of $\sim 16\%$ for TM-polarized light was measured at normal incidence at $\lambda = 796$ nm, and off-resonant reflection was below 1%, which is a result of some antireflection action of the photore sist film on top of the TiO$_2$ waveguide film. Although the maximal reflectance is far from 100%, it may be not a big problem for using such a mirror with a semiconductor laser. Because of the high optical gain in semiconductors, high-power lasers usually are designed to have front-mirror reflection in the range of 5–15% only. Anomalous reflection for TE-polarized light was considerably stronger. This usually happens because the radiative losses for TE-polarized modes are typically stronger than for TM. However, in preparing the experiment with a semiconductor laser (see the inset in Fig. 3), we studied anomalous reflection of TM-polarized light. Because the plane of the waveguide grating is normal to the plane of the semiconductor laser, the TE mode of the laser is coupled to the TM mode of the waveguide mirror. The FWHM of the 795-nm peak was found to be 0.22°. Fitting analysis by use of the Voigt function revealed that the Gaussian component of the peak profile is roughly twice as strong as the Lorentzian component. This difference may be attributed to the peak broadening associated with waveguide and (or) grating nonuniformity within the measuring spot ($\sim 3$ mm in diameter) and (or) slightly inaccurate wavelength tuning.

To prove the concept of using a waveguide grating mirror with a large-area semiconductor laser, we placed a sample a short distance in front of the laser’s output facet. Laser emission through the waveguide grating mirror was studied with a Hewlett-Packard HP70951B optical spectrum analyzer with a spectral resolution of 0.1 nm. Because of the heat-sink geometry, the shortest possible distance in our experiment was 2 $\mu$m, although we observed that the waveguide grating mirror affected the laser performance at a mirror–laser separation of as much as 5 $\mu$m. We used a commercially available (SDL 2300 series) wide-area semiconductor lasers with a nominal wavelength of 798 ± 3 nm and active stripe widths of 50, 100, and 200 $\mu$m. The resonator length was estimated to be $\sim 1$ mm, and the reflectivity of the output facets was $\sim 10\%$. We adjusted the lasers’s temperature to shift the low-pump emission spectrum closer to the waveguide grating’s reflection peak. We observed that the emission spectrum becomes modified when the grating mirror approaches closer to the laser. This change is most evident if the pumping current is within 3% above threshold. As shown in Fig. 3, the laser operating in superluminescence regime without the grating mirror emits in single longitudinal mode when the waveguide mirror is installed. These particular spectra were measured for a laser with a 50-$\mu$m-wide stripe and grating–facet separation of $\sim 2$ $\mu$m. The threshold current of the laser (380 mA free running) was found to decrease by approximately 1% when the grating was installed. With careful adjustment of the grating’s position and orientation with respect to the laser, we got more than 20-dB suppression of sidemodes. When the pump current

![Fig. 2. Angular reflectance spectra measured at different wavelengths.](image1)

![Fig. 3. Emission spectra with (solid curve) and without (dashed curve) the waveguide grating mirror. The inset shows the geometry of the experiment.](image2)
increased to more than 3% above the threshold, the spectrum became unstable and multimode, similar to the free-running laser.

We also observed narrowing of the far-field emission pattern correlated with the spectral narrowing. Figure 4 shows the far-field distribution of a laser with a butt-coupled waveguide grating mirror. For comparison, without this mirror the far field has a nominal width of ~12°. The far-field distribution has a complex shape. We typically observed an asymmetric picture, with one major lobe and a few additional lobes of smaller intensity. It is still an open question how to optimize the resonator and the waveguide-grating mirror parameters to achieve single-lobe, narrow far-field emission. However, the qualitative effect of using the waveguide-grating mirror is evident: It provides an increase in brightness with respect to the laser without the waveguide grating mirror.

All the reported results (emission spectrum and far-field pattern) depend critically on laser-grating alignment. Because spectrum narrowing was observed close to the threshold, the output power was low, typically within 10 mW. However, the importance of the reported results is in a qualitatively new approach to an important problem of spectral and spatial filtering in semiconductor lasers. Operation of a laser with additional feedback, in general, is a complex function of the number of parameters, although the mirror property seems to be the major factor for the case considered here. We believe that the range of stable operation as well as the sidemode-suppression ratio can be improved if one uses mirrors with higher reflectivity, reduces reflectance of the laser’s facet, and avoids diffraction losses by integrating the laser and the mirror.

In conclusion, our experiments have shown that a waveguide grating mirror can control the emission spectrum and the far-field emission pattern of a large-area semiconductor laser. This demonstration opens a new approach to the design of very compact semiconductor lasers operating in single-frequency–single-mode regime.

This work was supported by a Wayne State University Research Award. We acknowledge fruitful discussions with Yang Zhao of Wayne State University and John Marcianite of the Air Force Research Laboratory at Kirtland Air Force Base. I. A. Avrutsky’s e-mail address is avrutsky@ece.eng.wayne.edu.

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