Very narrow spectral filters with multilayered grating-waveguide structures

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Promising configurations for grating-waveguide structures are presented. In these structures, the grating layer, which is normally adjacent to the waveguide layer, is displaced by means of an intermediate layer, resulting in significant reduction of losses and weaker coupling. This leads to very narrow spectral bandwidths and high contrast ratios. Experimental results reveal that the spectral bandwidths can be as low as 0.1 nm with contrast ratios greater than 1000, suggesting that these grating-waveguide structures could be useful for optical communication networks. © *2000 American Institute of Physics.* [S0003-6951(00)04037-7]

Diffraction anomalies from gratings have been investigated for many years. They were originally observed by Wood,[1] and theoretically investigated by a number of researchers who dealt with the resonance behavior in reflection gratings.[2–7] These investigations have been expanded to include resonance anomalies in grating-waveguide structures (GWS), and new theoretical and experimental developments.[8–10]

GWS have a multilayer configuration, the most basic of which is comprised of a substrate, a thin dielectric waveguide layer, and an additional layer in which a grating is etched, as shown in Fig. 1. When such a GWS is illuminated with an incident light beam, part of the beam is directly transmitted and part is diffracted and subsequently trapped in the waveguide layer. If the transverse dimensions of the GWS are somewhat larger than the incident light beam, then the trapped light is completely confined and little if any escapes from the edges of the structure. Some of the trapped light is then rediffracted outward by the grating, so that it interferes destructively with the transmitted part of the light beam. At a specific wavelength and angular orientation of the incident beam, the structure ''resonates;'' that is, complete interference occurs and no light is transmitted. The spectral bandwidth of the resonance depends on geometrical parameters such as the grating depth, duty cycle, and thickness of the waveguide layer, as well as on optical parameters such as the refractive indices of the different layers.[10] In general, the resonance bandwidths are limited by the losses that are caused by material and fabrication defects. Typical bandwidths ranged from 0.25 to 3 nm at resonance wavelength of 1.55 μm.[10]

In this letter we resort to a different GWS configuration, in which the coupling of light into and out of the waveguide is reduced and the losses are significantly decreased. Accordingly, the resonance bandwidths can be much narrower than hitherto possible, so that GWSs become attractive for advanced spectral filtering and modulation applications.

The dominant losses result from the etching process involved in the formation of the grating layer. Specifically, the surface of the grating layer is excessively rough, due to inherent nonuniformities in the etching process. This surface roughness causes undesired scattering of light that is trapped in the waveguide, and thereby sets a lower limit on the resonance spectral bandwidth that can be obtained. Moreover, some of the light is scattered to higher evanescent diffraction orders, thereby reducing the light in the desired resonance mode that propagates in the waveguide.

To reduce losses we modified the GWS configuration, so the grating layer is separated from the waveguide layer by a buffer layer which serves also as a stop layer of the etching process. By separating the waveguide and grating layers, it is possible to optimize and control their thicknesses to a much higher degree (to an accuracy of several atomic layers), and essentially eliminate the relatively rough surfaces at the interface between the grating and the waveguide layers. The separation of the waveguide and the grating layers also partly changes the role of the grating layer. In the original configuration, both the grating and waveguide layers guided the mode trapped in the GWS. In the modified configuration, only the waveguide layer guides the mode, whereas the grating layer only diffracts the incident field and the propagating mode through interaction with the modal evanescent field. In such a modified configuration, an increase of the buffer layer thickness results in an exponential decrease of the coupling efficiency. Thus, in order to obtain a predetermined spectral bandwidth for a structure with a certain buffer layer thick-

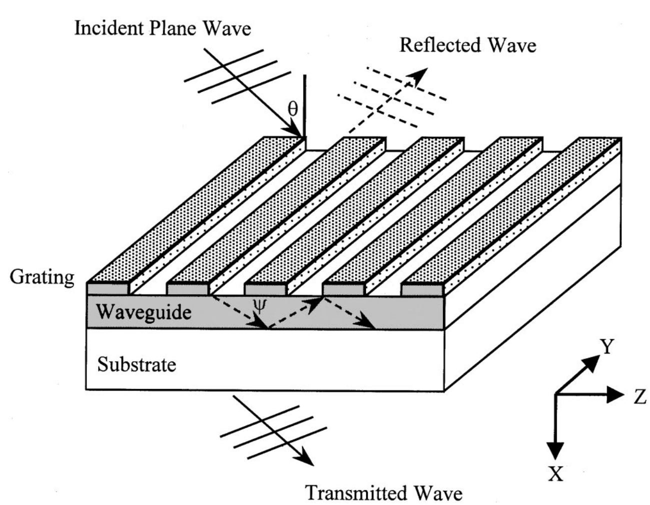

FIG. 1. Basic configuration of a grating-waveguide structure (GWS).

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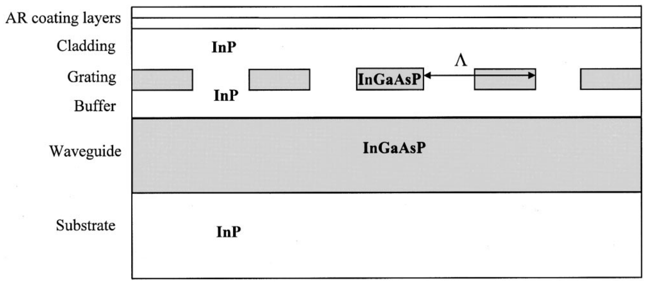

FIG. 2. A representative configuration of the modified GWS for obtaining very narrow and ultranarrow spectral resonance bandwidths.

ness, it is necessary to resort to a thicker grating layer, when compared to a usual configuration with adjacent waveguide-grating layers.

We designed and fabricated several GWSs, with our modified geometric configuration, so as to obtain narrow and ultranarrow spectral resonance bandwidths. We determined the optical and geometrical parameters in accordance with a numerical model that is based on the exact eigenfunction approach and Maxwell's equations,[11] and used InP/InGaAsP materials to design and fabricate GWSs to operate in the 1.55 μm region. A representative modified GWS configuration is shown in Fig. 2. The substrate is of InP material, on which a waveguide layer of InGaAsP is grown by metal-organic chemical-vapor deposition (MOCVD). Then a buffer layer of InP and a layer of InGaAsP are grown. Using photolithographic techniques, depositing a photoresist layer, exposure through e-beam, and subsequent etching, a grating was formed in the upper InGaAsP layer. Thereafter, a cladding layer of InP was deposited, smoothing the surface roughness at the interface between the grating and the InP buffer layers. The usual surface roughness at the interface between the waveguide and grating layer was eliminated almost entirely by the regrowth process. Moreover, this regrowth technique resulted in accurately controlled layer thicknesses dependent on the nominal accuracy of the MOCVD, i.e., several atomic layers. Finally, antireflection coating layers were deposited on top of the structure to decrease considerably Fresnel reflection leading to a high contrast ratio of the on-resonance power reflection over the off-resonance power reflection. It should be noted that since these antireflection layers are placed well above the waveguide layer they hardly interact with the guided mode through its modal evanescent field,

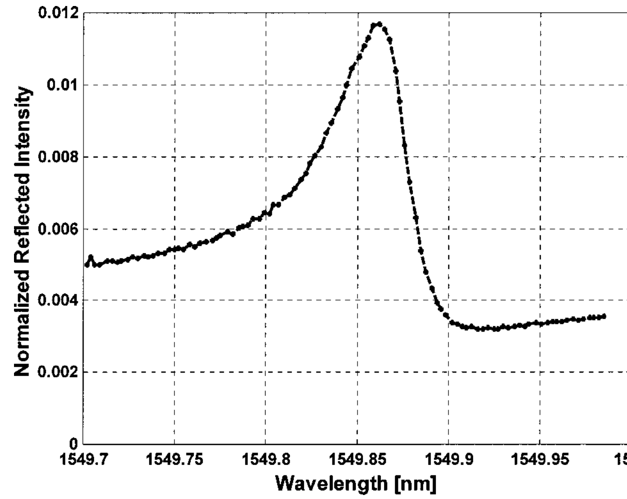

FIG. 4. Experimental normalized reflected intensity as a function of wavelength, for a GWS designed to have ultranarrow spectral resonance bandwidth.

and have little if any influence on the resonance spectral bandwidth. The grating period Λ for the different samples ranged between 470 and 477 nm, according to the desired resonance wavelength.

For the GWSs, designed to have very narrow widths of 0.09 nm at full width at half maximum (FWHM), the thicknesses of the waveguide, buffer, and grating layers were 400, 10, and 50 nm, respectively. For the GWSs, designed to have ultranarrow spectral widths of 0.005 nm at FWHM, the thicknesses of the waveguide, buffer, and grating layers were 400, 40, and 10 nm, respectively. We calculated and experimentally measured the resonance behavior of the different GWSs. The experimental setup included a tunable semiconductor laser, and a pair of detectors that measured both the incident and the reflected intensities in order to determine the normalized reflected intensity. The spectral resolution at the output was better than 0.003 nm. Calculation and measurements were performed with a TE polarized incident beam, oriented at normal and close to normal incidence angle with respect to the GWSs.

Representative calculated and experimental results are shown in Figs. 3 and 4. Figure 3 shows the normalized reflected intensity as a function of wavelength, for a GWS designed with a very narrow resonance bandwidth. The cal-

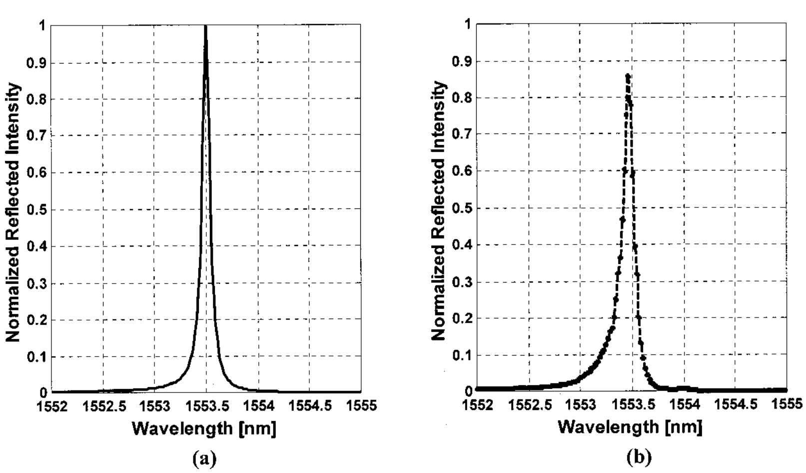

FIG. 3. Normalized reflected intensity as a function of wavelength, for a GWS having very narrow spectral resonance bandwidth. (a) calculated results; (b) experimental reesults.

culated spectral resonance bandwidth, shown in Fig. 3(a) is 0.09 nm at FWHM. The measured spectral resonance bandwidth, shown in Fig. 3(b), is 0.12 nm at FWHM, indicating that the finesse is 13 000. The peak reflected intensity was measured to be 86% of the incident intensity. The ratio between peak intensity at resonance to that at off-resonance by 1 nm, is better than 1000. As evident, the experimental results are in good agreement with the calculated results. Some asymmetry of the resonance shape is observed both in the theoretical and experimental results. We believe it is caused by interference between the modes inside the waveguide.[12]

Figure 4 shows the experimental normalized reflected intensity as a function of wavelength for a GWS designed to have an ultranarrow bandwidth of 0.005 nm. As evident the resonance is only barely detectable above the background. The spectral resonance bandwidth at FWHM is about 0.05 nm, rather than the designed 0.005 nm and the peak normalized reflected intensity is only about one percent. We attribute these poor results to the losses that still exist in the GWS, whose effect is much greater with the ultranarrow resonance bandwidths. As evident, the effect of such losses on the performance of the GWS resonance are the broadening of its spectral bandwidth and the lowering of its peak. The losses result from several different causes, which include: (a) nonuniformities in the thickness of the waveguide layer, introduced during the deposition process; (b) stitching errors between adjacent electron beam fields, resulting from distortions that occur during the grating recording process; and (c) escaping of a small fraction of the guided light from the edges of the GWS. We believe, that as the fabrication technology improves it would be possible to further reduce the losses so as to reach good ultranarrow bandwidth performances.

To conclude, we developed GWS configurations that lower the inherent losses and considerably improve the performance of GWSs. We have experimentally demonstrated that very narrow spectral resonance bandwidths of 0.12 nm at FWHM in the wavelength region of the 1.55 μm can be achieved, and noted some limitations in reaching ultranarrow spectral bandwidths. These resonances also have very high contrast ratios (>1000), a property which makes them attractive to many applications of optical communications systems, such as optical modulators and dynamic spectral filters for wavelength division multiplexing (WDM) applications.

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