Cavity-resonator-integrated guided-mode resonance filter in channel waveguide

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Abstract: A cavity-resonator-integrated guided-mode resonance filter (CRIGF) consisting of a grating coupler and a pair of distributed Bragg reflectors in a channel waveguide is proposed for a narrow-band reflection spectrum with a small aperture. A channel waveguide structure and grating pattern of the device were simultaneously formed by the electron-beam direct-writing lithography. A full-width at half-maximum of reflection spectrum of the fabricated CRIGF was about 0.3 nm with the maximum reflectance of about 30%. A reflection phase varied by almost 2π for wavelength change of 1 nm.

Keywords: wavelength filters, optical waveguides, grating couplers, guided-mode resonance, distributed Bragg reflectors, waveguide resonators

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

References

1 Introduction

A guided-mode resonance filter (GMRF) consisting of a surface grating in a thin-film waveguide shows a narrow-band reflection spectrum for an incident wave from free space [1, 2, 3, 4, 5, 6, 7], where the grating acts as a grating coupler (GC) that excites and out-couples a guided wave at a coupling wavelength, namely, a resonance wavelength. GMRF can be fabricated by a few-layer deposition followed by surface patterning and give an advantage of high fabrication-throughput in comparison with multilayer dielectric mirrors (MDM). It is much easier to integrate multiple filters for different wavelengths on the same substrate than the case of MDM because the reflection wavelength can be controlled by the grating period. GMRF has attracted much attention in applications to laser mirrors as well as wavelength filters.

The high reflectance of GMRF results from the cancellation of the direct transmission of the incident wave by the radiation of the guided wave by the grating. In other words, a sufficient guided-wave power should be excited for the cancellation. The excitation efficiency depends on the coupling coefficient and length of the grating. A large coupling coefficient needs a deep refractive-index modulation. Therefore, GMRF formed with dielectric materials of low refractive indices normally needs a sub-millimeter-size aperture as well as a sub-millimeter-size incident beam diameter [8, 9]. Miniaturization of GMRF would provide an ideal filter applicable to a lens-less direct coupling to an optical fiber or waveguide end, and is attractive for constructing a very compact fiber or waveguide laser for example. Utilization of the second-order diffraction of the grating was discussed for the miniaturization, but still needs a beam width of tens of microns [10].

Recently, we have proposed a new type of GMRF, namely, a cavity-resonator-integrated guided-mode resonance filter (CRIGF), consisting of a GC and a pair of distributed Bragg reflectors (DBRs) for an aperture miniaturization [11, 12, 13]. The basic characteristics of CRIGF integrated in a slab waveguide were demonstrated with use of linear and uniform gratings [12, 13, 14]. However, a wavefront deformation of the guided wave due to diffraction effect becomes serious as the incident beam width is reduced, increasing loss in the resonator and reducing the reflectance of CRIGF. Then we investigated curved gratings which form a cavity resonator for a standing guided wave propagating with divergence due to diffraction in the slab waveguide [15]. We also discussed a reflection phase of the CRIGF which is a crucial factor in designing it as a laser mirror, and

found a large dependence of a reflection phase variation on wavelength [16].

On the other hand, utilization of a channel waveguide confines a guided wave laterally and gives a smaller footprint than the case using a slab waveguide. However, a channel waveguide requires generally additional processes in fabrication. In this paper, we discuss CRIGF having a channel waveguide structure and grating pattern of the same height in order to form those simultaneously without additional channel patterning processes. The device of a 10-μm-size aperture was designed for operation at 846-nm wavelength. The reflection spectrum and wavelength-dependence of reflection phase of a fabricated device were characterized experimentally.

2 Basic configuration and operation principle

A schematic view of the cross-sectional structure of CRIGF is illustrated in Fig. 1. GC is integrated between a pair of DBRs with phase-adjusting gaps. Grating corrugation is formed on a guiding core layer on a substrate.

![Fig. 1. Basic configuration of CRIGF and wave coupling.](image)

Wave propagations are also shown in Fig. 1. We consider here that a transverse-electric (TE) wave, of which electric field is parallel to the grating lines, is vertically injected to CRIGF from the air. The incident wave of the resonance wavelength is partially coupled by GC to guided waves propagating contra-directionally with each other, and partially transmits to the substrate. The excited guided waves are accumulated by a resonance effect and coupled out by the same GC to radiation waves propagating into the air and the substrate. The radiations are superposed to the direct reflection and transmission of the incident wave. The phase-adjusting gap between GC and DBR is determined so that the radiation waves from forward and backward guided waves are phase-matched with each other and have the opposite phase against the direct transmission wave. We named this condition “in-phase resonance”. When the reflectance of both DBRs is unity, the guided wave power is accumulated enough to cancel the direct transmission. As a result, only the reflection remains. Thus, CRIGF acts as a high-efficiency mirror at the in-phase-resonance wavelength even with a micrometer-size aperture.

3 Design

CRIGF of 10-μm aperture in a channel waveguide was designed at the in-phase-resonance wavelength of 846 nm. The incident wave was assumed to
have the uniform intensity but to be limited inside the aperture. A schematic perspective view of CRIGF in a channel waveguide is shown in Fig. 2. A GeO$_2$:SiO$_2$ guiding core layer of refractive index of 1.540 and electron-beam (EB) resist cladding layer of a refractive index of 1.550 were stacked on a SiO$_2$ glass substrate of a refractive index of 1.452. The cladding layer is shaped into a 10-μm-width strip to form a channel waveguide. Gratings with line/space ratio of 1:1 were formed by corrugation of the cladding layer. The strip-shaped cladding layer and gratings can be simultaneously formed by the same lithography when they have the same height. Higher grating tooth is better for higher reflection of DBR with a shorter coupling length. The height of gratings was chosen to be 250 nm, which was the highest value limited by our lithography system. The guiding core layer should be thick to reduce propagation loss due to boundary scattering. On the other hand, a single-mode condition is preferable because a multi-mode waveguide may cause multiple resonance wavelengths. Then the thickness of the guiding core layer was chosen to be 700 nm so that a single-mode waveguide is formed before channel patterning. The designed channel waveguide supports laterally-multiple guided modes. However, higher-order modes than the fundamental one are hardly excited due to large mismatch in electric-field profile with the incident wave. Then we can predict the performance as if it is a single-mode waveguide.

A cross-sectional structure of the designed CRIGF is illustrated in Fig. 3. The effective refractive index of the fundamental guided mode was calculated to be 1.496. The grating periods of GC and DBR were determined to be 566.0 nm (=λ) and 283.0 nm (=λ/2), respectively. The phase-adjusting gap was 70.75 nm (=λ/8). The radiation decay factor of GC was calculated to be 4.24 mm$^{-1}$. The reflectance of each DBR was calculated to be higher than 99.99% with a coupling length of 245 μm. Reflection and transmission spectra predicted by an analysis model based on the coupled-mode theory [11] are shown in Fig. 4. The maximum reflectance and full-width at half-maximum (FWHM) were expected to be almost 82% and 0.33 nm, respectively.
Fabrication

A GeO$_2$:SiO$_2$ guiding core layer was deposited on a SiO$_2$ glass substrate by plasma-enhanced chemical vapor deposition. A positive EB resist was spin-coated on the deposited layer. Surrounding area of the strip and grooves of the gratings were exposed by EB and removed by developing. Figure 5 shows an optical microscope photograph and scanning electron microscope image of the fabricated CRIGF. The line/space ratio in GC part was about 1:1. The ratio of 1:1 in DBR part could not be obtained. Even so, the predicted reflectance of the fabricated DBR was still higher than 99.99%.

Optical measurements

5.1 Reflection spectrum

An experimental setup for measuring a reflection spectrum is illustrated in Fig. 6. A beam launched from a wavelength-tunable laser diode (LD) was condensed by a lens to 10-μm diameter on the GC surface. The reflected
Fig. 5. (a) Optical microscope photograph and (b) scanning electron microscope image of the fabricated CRIGF.

Fig. 6. Experimental setup for measuring a reflection spectrum of fabricated CRIGF.
beam from the CRIGF was collimated by the same lens and reflected by a beam splitter (BS) to a CCD camera. The reflectance was estimated from the measured reflection power by comparison with the Fresnel reflection from the surface of the fabricated device without the CRIGF pattern, which was theoretically estimated to be 5.8%. The measured reflection spectrum is shown in Fig. 7. The single-peak reflection spectrum was confirmed with the peak wavelength of 846.84 nm which is expected by assuming the guided-mode index is about 0.1% larger than the design. The maximum reflectance was measured to be about 30% which is expected by assuming DBR reflectance of 89%. The FWHM of the reflection spectrum was about 0.3 nm in accord with the theoretical prediction.

![Fig. 7. Measured reflection spectrum of fabricated CRIGF.](image1)

![Fig. 8. Experimental setup for measuring a reflection phase variation of fabricated CRIGF.](image2)
5.2 Reflection phase variation
An experimental setup for measuring a reflection phase variation is illustrated in Fig. 8. A beam launched from a wavelength-tunable LD was divided by a BS to two beams. One beam was condensed onto the CRIGF by a lens. The reflected beam from the CRIGF was collimated by the same lens and reflected by the BS to a CCD camera. The other beam was reflected by a metal mirror with a slightly tilted angle to the CCD camera. These two beams formed interference fringes. Figure 9 shows examples of obtained interference fringes. The interference fringe shifted when a wavelength changed. A fringe shift of the fringe period indicates a reflection phase variation of $2\pi$. Measured dependence of the reflection phase variation on wavelength is shown in Fig. 10. The reflection phase varied by about $2\pi$ when the wavelength was swept over the resonance wavelength region.

![Fig. 9. Observed interference fringes.](image)

![Fig. 10. Measured reflection phase variations of fabricated CRIGF.](image)
6 Conclusions

A CRIGF in a channel waveguide was discussed for the first time. The channel waveguide enables high-density integration in comparison to the configuration using curved gratings in a slab waveguide. A strip-shaped cladding layer on a planar guiding core layer constituting a channel waveguide was designed to have the same height as integrated gratings for avoiding additional channel patterning processes. A device of 10-μm aperture was fabricated by planar processes including EB direct-writing lithography. A narrow-band reflection spectrum of the fabricated device was experimentally demonstrated with the maximum reflectance of about 30%. A reflection phase variation of almost $2\pi$ was also obtained for wavelength change of 1 nm.

Acknowledgments

The authors would like to express sincere thanks to Prof. H. Kikuta and Mr. Y. Minamino at Osaka Prefecture University for their support on EB direct writing process.