Integrated W-type structure for spectral and spatial filtering of optical radiation propagating in a slab waveguide

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Abstract. We present a simple and compact integrated narrowband filter that enables spectral or spatial filtering of optical radiation propagating in a slab waveguide. The filter consists of two grooves on the waveguide surface and constitutes an integrated analogue of the so-called W-type structure. The filtering is performed in transmission at oblique incidence due to the excitation of a leaky eigenmode of the structure localized at a ridge separating the grooves. For the considered parameters, neither “parasitic” out-of-plane scattering nor polarization conversion occurs, and strictly zero reflectance and unity transmittance are achieved at resonant conditions. The quality factor and location of the resonance can be controlled by changing the widths of the grooves and of the ridge between them, respectively. The proposed filter may find applications in novel devices of integrated nanophotonics.

1. Introduction
Spectral and spatial filters that selectively transmit or reflect incident radiation are indispensable in various optical devices including, among others, spectrum analyzers, wavelength multiplexers and demultiplexers, and remote sensing systems. In many integrated optoelectronic systems, the filtering is performed in a slab waveguide [1–4]. Such geometry is suitable for the creation of fully integrated optical devices. Waveguide-integrated Bragg gratings (BGs) and phase-shifted Bragg gratings (PSBGs) are widely used for spectral filtering of optical radiation propagating in slab waveguides [1]. Recently, novel structures that can be applied in integrated spectrometers, the so-called digital planar holograms (DPHs), were proposed [3]. DPHs comprise a sophisticated superposition of narrowband low-contrast curvilinear BG-based reflectors fabricated on the surface of the guiding layer.

In this work, we propose a planar spectral filter operating in transmission and consisting of two grooves on the surface of a slab waveguide. In contrast to the BG- or PSBG-based filters and DPHs, our filter has a much simpler geometry and is substantially more compact.

2. Geometry of the structure
The proposed filter shown in figure 1(a) is a planar version of dielectric three-layer W-type resonant structure, which was studied in [5] for achieving large optical field enhancement over a large volume.
The effective refractive index profile of the structure is shown in figure 1(b). The structure consists of two grooves (length $h_{cl}$) on the surface of a single-mode dielectric ridge waveguide (dielectric permittivity $\varepsilon_f$, thickness $w_{inc} > w_g$) and a ridge (length $h_{wg}$) separating them. Theoretical analysis performed by the present authors [6, 7] shows that, similarly to the conventional W-type structure [5], the investigated planar structure supports a leaky eigenmode localized at the central ridge, which in this case acts as a resonant cavity. The excitation of this mode leads to the appearance of resonant transmittance peaks and reflectance dips, which suggests that this effect can be used for spectral or spatial filtering of the incident radiation propagating in the waveguide.

![Figure 1. Geometry of the proposed two-groove planar filter (a) and the effective refractive index profile of the structure (b). The dimensions in (a) and the values in (b) correspond to one of the examples considered below.](image)

3. Results and discussion

Let us now numerically investigate the performance of the proposed integrated W-type filter. In the simulations, the following parameters were used: free-space wavelength $\lambda_0 = 630$ nm, TE-polarization, $\varepsilon_f = 3.32^2$ (GaP), $\varepsilon_i = 1.45^2$ (fused silica), $\varepsilon_w = 1$, $w_{inc} = 100$ nm. At these parameters, the considered slab waveguide is single-mode. The filter consists of two grooves with depth $w_{inc}/2$ (so that $w_g = w_{inc}/2 = 50$ nm) and a ridge between them. In the case of TE-polarization, the effective refractive index of the incident guided mode and the mode in the ridge region is $n_{eff}(w_{inc}) = n_{eff}(w_g) = 2.7563$, while the effective refractive index in the groove region amounts to $n_{eff}(w_g) = 2.19$.

As mentioned above, the resonances occurring in the proposed filter are associated with the excitation of a leaky eigenmode localized at the central ridge of the structure and propagating along the $x$ axis. This eigenmode is close to a mode of a photonic rib waveguide. The quality factor of the resonance (the width of the resonant peak) is determined by the width of the grooves $h_{cl}$. To illustrate this, we calculated the angular and wavelength transmission spectra of the investigated structure at two groove widths $h_{cl} = 400$ nm and $h_{cl} = 600$ nm (figure 2). At these groove widths, the angular and spectral widths of the resonant peaks differ by approximately 10 times. The width of the ridge is fixed and equals $h_{wg} = 100$ nm. The spectra were calculated using an in-house implementation of the aperiodic rigorous coupled-wave analysis (aRCWA) technique [8]. RCWA, also called the Fourier modal method, is an established numerical technique for solving Maxwell’s equations. The angular spectra in figure 2(a) were calculated at a fixed wavelength $\lambda_0 = 630$ nm. The transmittance reaches unity at the angles of
incidence \( \theta_1 = 55.201^\circ \) (at \( h_i = 400 \) nm) and \( \theta_2 = 55.226^\circ \) (at \( h_i = 600 \) nm). The full width of the resonant transmittance peaks at half maximum (FWHM) amounts to \( \Delta \omega_1 = 0.091^\circ \) and \( \Delta \omega_2 = 0.0092^\circ \) at \( h_i = 400 \) nm and \( h_i = 600 \) nm, respectively. The dependence of the FWHM of the resonant peak on the width \( h_i \) is shown inset. Let us note that the angles of incidence \( \theta_{1,2} \) depend on the thickness of the waveguide in the groove regions \( w_g \). With a decrease in \( w_g \) (decrease in \( n_{eff} (w_g) \)), the angles \( \theta_{1,2} \) also decrease, and at \( w_g = 0 \) \( (n_{eff} (0) = 1 \) in the groove regions) they approach 33°.

![Transmittance vs. \( \theta - \theta_0 \) (a) and Transmittance vs. \( \lambda \) (b)](attachment:image)

**Figure 2.** Angular (a) and wavelength (b) transmission spectra of the studied filter at \( h_i = 400 \) nm (dashed blue curves) and \( h_i = 600 \) nm (solid red curves). The insets show the FWHM of the resonant peaks vs. \( h_i \).

It is worth noting that in the case of incidence of a TE-polarized mode at angles of incidence greater than \( \theta > 46.34^\circ \), there is neither out-of-plane scattering nor polarization conversion in the structure. Indeed, one can show that at \( \theta > 46.34^\circ \) the slab waveguide does not support any propagating TM-polarized modes with the propagation constants \( k_{TM} > k_{x,TE} \), where \( k_{x,TE} = k_0 n_{eff} (w_ac) \sin \theta, k_0 = 2\pi/\lambda_0 \) is the tangential component of the wave vector of the incident TE-polarized mode. Moreover, the plane waves under and over the structure (in the substrate and superstrate regions with dielectric permittivities \( \varepsilon_s \) and \( \varepsilon_u \) ) with the \( x \) wave vector component \( k_{x,TE} \) are evanescent. Thus, the energy of the incident TE-polarized mode will be divided only between two modes (reflected and transmitted) having the same polarization. Due to this, strictly zero reflectance and unity transmittance are achieved in the structure at resonant conditions.

The wavelength spectra in figure 2(b) were calculated at the angles of incidence \( \theta_1 \) and \( \theta_2 \) taking into account the dielectric permittivity dispersion of the core layer. FWHM values of the resonant peaks
are $\Delta_{cl,1} = 3.0 \text{ nm} \ (\text{at} \ h_d = 400 \text{ nm})$ and $\Delta_{cl,2} = 0.3 \text{ nm} \ (\text{at} \ h_d = 600 \text{ nm}).$ Similarly to figure 2(a), the inset in figure 2(b) shows the FWHM of the peak vs. the width $h_d$.

Thus, the presented results confirm that the proposed integrated W-type structure can be utilized as a narrowband spectral or spatial filter. It is worth noting that the proposed structure is substantially more compact than the integrated filters based on BGs or PSBGs. In particular, in comparison with the integrated PSBGs designed for the waveguide configuration described above and providing transmittance peaks with the same spectral FWHM values, the total width of the proposed W-type structures $(2h_d + h_{wg})$ is 2.5–5 times smaller.

4. Conclusion
In this work, we presented a simple and compact transmission filter consisting of two grooves on the surface of a slab waveguide and intended for spectral filtering of optical radiation propagating in the waveguide. The spectral filtering is performed due to resonant excitation of an eigenmode of the structure localized at the cavity corresponding to the ridge between the grooves. The possibility to control the spectral width and location of the resonant peak by changing the widths of the grooves and the ridge between them was demonstrated. Moreover, for the considered parameters, there is no unwanted parasitic scattering and polarization conversion in the filter. The proposed structure can be used for the creation of planar analogues of linear variable filters for waveguide-integrated spectrometers.

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References
[1] Haus H A 1984 Waves and Fields in Optoelectronics (Hemel Hempstead: Prentice-Hall)
[2] Mossberg T 2001 Opt. Lett. 26 414–6
[3] Calafiore G, Koshelev A, Dhuey S, Golstov A, Sasonov P, Babin S, Yankov V, Cabrini S and Peroz C 2014 Light: Sci. & Appl. 3 e203
[4] Ma X, Li M and He J J 2013 IEEE Photon. J. 5 6600807
[5] Sainidou R, Renger J, Teperik T V, González M U, Quidant R and García de Abajo F J 2010 Nano Lett. 10 4450–5
[6] Doskolovich L L, Bezus E A and Bykov D A 2018 Photon. Res. 6 61–5
[7] Doskolovich L L, Bezus E A, Golovastikov N V, Bykov D A and Soifer V A 2017 Opt. Express 25 22328–40
[8] Silberstein E, Lalanne P, Hugonin J-P and Cao Q 2001 J. Opt. Soc. Am. A 18 2865–75