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GUIDED MODE RESONANCES FOR ANGULAR AND SPECTRAL FILTERING

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The development of devices based on compact waveguides is a rapidly evolving field. A unique variation of such devices is the Fano-like resonance dielectric spectral and spatial filtre, made from a dielectric conformal thin film on a surface relief grating. It can be used in a normal (or oblique) angle-of-incidence configuration. This device facilitates directional selectivity, which is useful for transverse-mode cleaning in short optical cavities. It can also be enhanced by using leaky-mode effects to produce even sharper spectral features. However, a perfect spatial filtre should be as invariant as possible in the spectral and enhanced angular domains. Here, we solved the inverse design problem to produce such an effect. Numerically, we tuned the surface profile of the substrate grating, assuming a conformal layer on top. This resulted in trapezoidal relief patterns followed by narrow flat-top angular features. The combination of leaky mode effect and enhanced device topology will enable efficient and useful devices with a bandwidth of 50 nm and even more in the future.

Keywords: nanophotonics, linear photonics, RCWA, Maxwell's equations, ion beam sputtering

1. Introduction

There exists a multitude of optical components recently developed that are thin on a wavelength scale and mimic the function of classical bulky elements, making complex optical and laser systems more compact [1]. Examples include meta-optical components such as metalenses based on metaatoms [2], surface relief holographic elements [3] and thin film grating elements [4]. They can replace classical Bragg gratings in a lossless dielectric configuration and are successfully used in compact laser systems such as vertical-cavity surface-emitting lasers (VCSELs) to stabilize their spectrum and emission direction [5].

An interesting mode of operation of such gratings is based on the Fano resonance that was studied almost a century ago [6] inside periodically modulated waveguide systems. The recent work reveals the existence of sharp reflection profiles in the zeroth-order angular spectra, which can be applied for spatial filtering in the angle domain [4, 7–14]. By varying the geometrical parameters of the waveguide, one could change the location of the resonance in the angular and spectral domains.

The flat-top reflection spectrum for incident electromagnetic plane waves can be achieved for the *s* polarized input [15]. Similar results are also observed for the *p* polarization [14]. However, numerical simulations show another phenomenon that was used to achieve broadband mirrors in the wavelength domain [16, 17]. The broadband reflection is achieved in high contrast thin film gratings but only for an optimal choice of periodic waveguide's geometrical parameters and materials: mainly a substrate and a thin film.

By observing the electric and magnetic field distributions within the structure, one concludes that the non-diffracting fields into the substrate are leaky with an exponentially decaying amplitude [18]. Judging from the numerical simulations of the angular zeroth-order reflection spectrum that was calculated in Ref. [17], a triangle-like symmetric reflection profile has been found in the angular-wavelength domain. Here leaky modes transform into the first-order diffracted orders by varying the angle of incidence of plane waves, although the top of reflection remains flat for broad angles. Such a result occurs in the Rayleigh anomaly regime [19], which is primarily tied with the phenomenon studied by Magnusson [15].

Another way of interpreting such an effect is through the energy redistribution between the diffraction orders when they become evanescent in transmission amplitude gratings. This effect can be calculated analytically for various forms of transmission gratings [20]. Here, we study the effect of leaky mode resonance in the periodically trapezium modulated waveguide and achieve narrow-band angular reflection in the broad spectral domain.

2. Angular filtering

The aforementioned effect could therefore be used for angular filtering in reflection. This way, the reflected beam becomes cleaner with a substantially reduced M^2 parameter. Such optimized filtering systems are also capable of functioning as low pass reflectors, as reported in Refs. [1, 21].

Because of the high contrast of refractive indices of the materials of the thin film, substrate and superstrate, the waveguide system acts as a wave trapping system. This concept is illustrated in Fig. 1(a). The discrete energy states of trapped waves in the thin film with a low leakage are identified as Fano resonances [4, 14].

By varying the width L of the potential well (or the geometrical thickness of the waveguide), the location of the Fano resonances in the (θ, λ_0) domain can be varied or a wide-band reflector could be achieved near the critical wavelength $\Lambda_x n_{sub}$, which is the edge of a continuum [14]. In the continuum (at higher frequencies), the energy of the incident wave is carried out onto diffraction or backward reflection in ±1 orders.

Both Fano and leaky types of resonances maximize reflection near 100% in the zeroth reflection spectrum, but the latter effect provides the continuum of leaking modes within the substrate that prohibit transmission. The angular filtering concept of the occurrence of leaky modes within the substrate material is visualized in Fig. 1(b). Higher angle

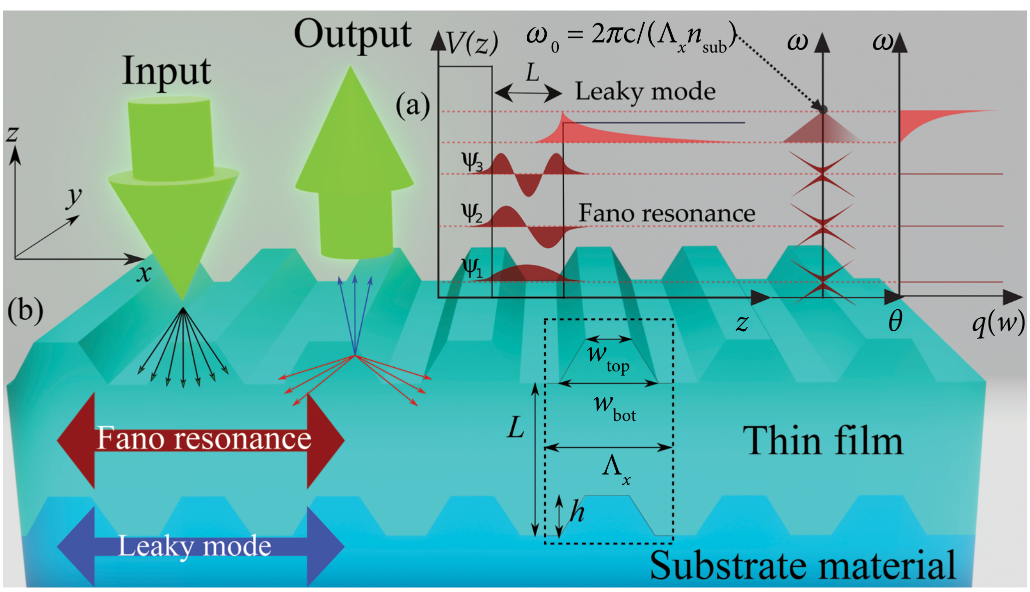

Fig. 1. The concept of angular filtering via reflection. Finite quantum well (a) for the trapped modes Ψ_{1-3} Fano resonances that are tuned by varying the thickness L of the waveguide. Leaky mode is localized near the interface of the asymmetrical well in the angular and frequency domain, producing triangular-like reflection. The design to realize such configuration of guided-mode resonance is the trapezium modulated waveguide (b).

components of the incident beam are diffracted, whereas the narrow part is reflected backward. Therefore, a lower divergence of the reflected beam compared to the input is achieved.

3. Numerical results

We consider a trapezium profile grating (shown in Fig. 1), but similar results are also achievable with other forms of gratings, such as harmonic, super-Gaussian [14]; however, perfect broad triangular spectra of reflection are realized via the trapezium modulated waveguide. The substrate material is ormocomp, which has a refractive index of $n_{sub} = 1.5$ and the added layer on top has $n = 2.25$ at the $\lambda_0 = 970$ nm vacuum wavelength. The refractive index of the film corresponds to Nb_2O_5. Other geometrical parameters, included in the trapezium profile grating, are bottom and top trench widths $w_{bot} = 0.195$ μm and $w_{top} = 0.375$ μm, respectively.

The design of the grating for angular filtering is carried out by two methods combined together. The first one is choosing the efficient solver capable to calculate diffraction efficiencies (all transmission and reflection orders), which is, for instance, 2D RCWA (rigorous coupled wave analysis) in combination with T matrix method implementation [22, 23] for fast and precise computations. The second one is the implementation of the global optimization method based on the genetic algorithm selected to minimize the merit function, shown in Eq. (1),

$$\ddot{u}(\ ,\Lambda_x,\ ) = -\int_{\theta_1}^{\theta_2} \frac{R_0^{\ddot{u}}\ (\theta)}{|R_0^{(\mathrm{id})}(\theta) - R_0^{(\mathrm{RCWA})}(\theta)|}, \quad (1)$$

where integration is performed from θ_1 to θ_2 for *s* polarization. For clarification, the *s* polarization contains the electric field propagating in parallel with the grating slab, whereas the *p* polarization is the perpendicular electric field.

The zeroth-order reflection is symmetrical in the angle domain, so the integration was performed from $\theta_1 = 0$ to $\theta_2 = 5$ deg. The goal is to obtain geometrical parameters, such as the modulation height

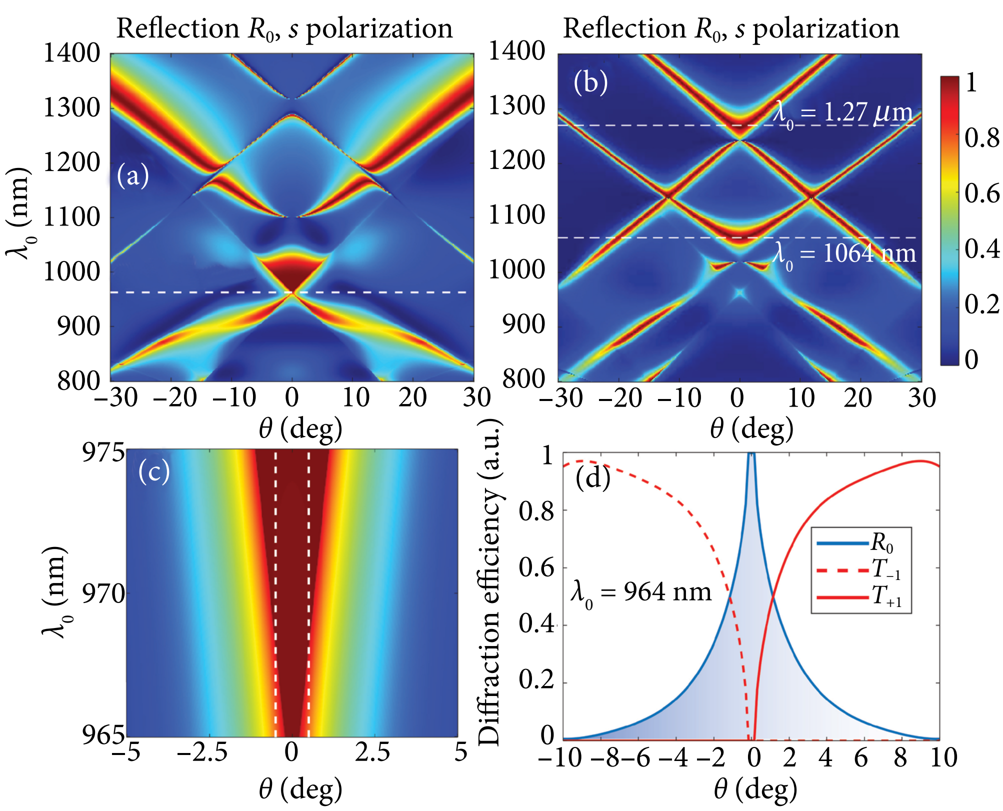

Fig. 2. Trapezium modulated waveguide zeroth-order (angle-wavelength) reflection spectra for $L = 580$ nm (a) of *s* polarized incident waves and *p* polarized waves (b). Continuous reflection angular spectrum is shown in (c), where the width between dotted lines corresponds to $\Delta\theta = 1$ deg. The (d) part represents diffraction efficiencies for R_0 and $T_{\pm 1}$ terms at $\lambda_0 = 964$ nm.

h (i.e. trench depth), the transverse period of grating Λ_x, as well as the thickness of the film L. The merit function is chosen in such a way that 100% reflection at the target wavelength $\lambda_t = 970$ nm (semiconductor laser wavelength [24]) is achieved. The interpretation of the merit function (Eq. (1)) is arranged in the following matter: the value of h denotes the coupling strength between spatial harmonics, and Λ_x (precisely $\lambda = \Lambda_x n_{sub}$) is responsible for the localization of the reference point from which leaky modes occur in the wavelength domain. By obtaining such parameters, the value of film thickness L is adjusted to expand continuous reflection (>99%) near $\lambda = \Lambda_x n_{sub}$.

To cancel higher angle terms, the Gaussian weight function $R_0^{(w)}$ is used to suppress reflection for higher angles of incidence, with its full width at half maximum $\Delta\theta = 1$ deg. The ideal shape of the desired reflection is $R_0^{(id)}$ with its width also at $\Delta\theta = 1$ deg. Its form is chosen to be rectangular. Finally, the optimized parameters are found: $h = 230$ nm, $\Lambda_x = 638$ nm and $L = 580$ nm for the s polarized input.

The achieved results of reflection are shown in Fig. 2(a–d). At the critical wavelength, the broadband reflection is obtained for 46 nm in the spectral domain for the s polarization, as well as encountering Fano-type reflections for the higher vacuum wavelength λ_0. The reflection spectrum for the p polarization (Fig. 2(b)), however, only contains Fano-type resonances, so the broadband reflection is polarization sensitive. Furthermore, the wavelength range where the optimization procedure was performed is 970 ± 5 nm, and the zeroth-order reflection remains flat in both angular and spectral domains, shown in Fig. 2(c). Here, the dashed curve shows $\Delta\theta = 1$ deg. Below the central wavelength (970 nm), at $\lambda_0 = 964$ nm, the diffraction efficiency dependence on the angle of incidence θ is shown in Fig. 2(d). In this case, only zeroth-order reflection dominates in the near to normal incidence. At the oblique incidence, only forward diffraction occurs, which is shown in red lines in Fig. 2(d). This type of phenomenon is known as Rayleigh–Wood anomaly [21].

It appears that the reflection in the angular and wavelength domain is completely triangle-like, which possesses a tip at the wavelength $\lambda_0 = \Lambda_x n_{sub} = 957$ nm. The location of this reflection profile can be red-shifted or blue-shifted at the wavelength domain by changing the transverse period of the modulated waveguide, which makes the location of triangle-shaped reflection easy to localize. Below such wavelength, $m = \pm 1$ transmission orders dominate.

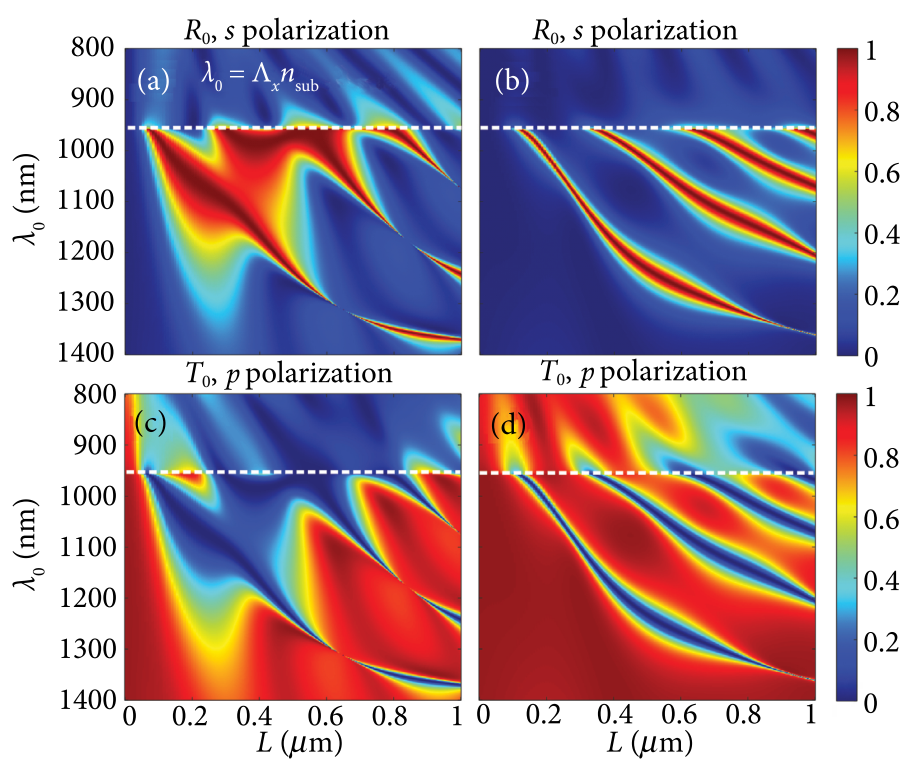

Fig. 3. Zeroth-order reflection (a, b) and transmission (c, d) spectra for the normal incidence of incoming plane waves for s and p polarizations.

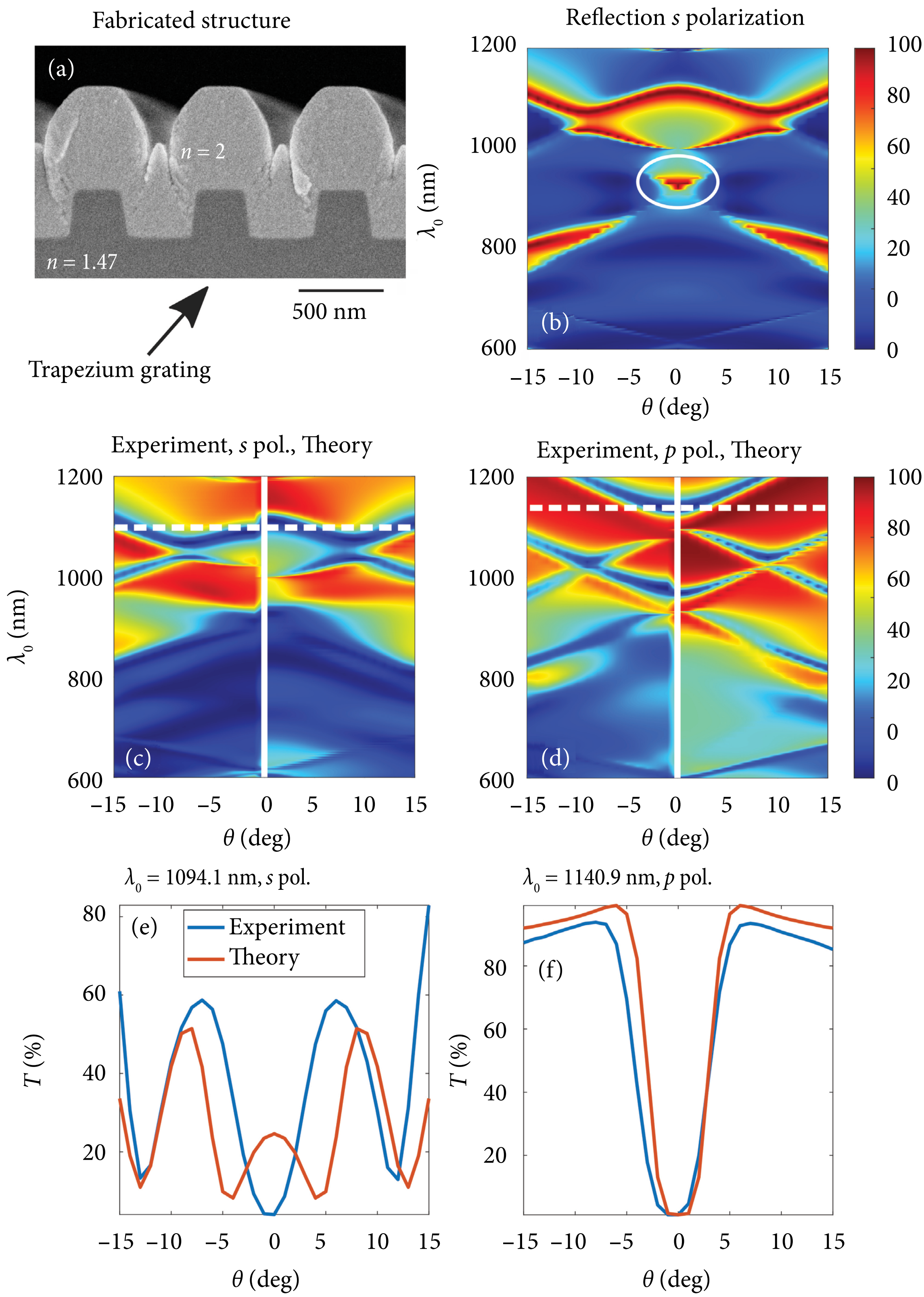

Fig. 4. Cross-section of the fabricated structure (a), the simulated zeroth-order reflection spectrum (b) with triangular reflection, the zeroth-order transmission comparison between the measured and simulated maps of *s* (c) and *p* (d) polarizations, as well as their angular profiles in (e) and (f), respectively.

Moreover, since the geometrical thickness *L* corresponds to the width of the potential well (shown in Fig. 1(a)), the normal incidence provides the degeneracy of guided-mode resonance [14].

In this case, the broadband flat top reflection can be achieved by varying the geometrical thickness of the thin film (from 0 to 1 μm). Therefore, the reflection region for the *s* polarization with the highest width (46 nm) can be found, which is shown in Fig. 3(a). Fig. 3(b) is the zeroth-order reflection spectrum for the *p* polarization, showing only Fano-type reflections. The zeroth-order transmission for *s* and *p* polarizations (Fig. 3(c, d)) beyond the continuum wavelength represents diffraction into the substrate for the normal incidence. A smaller fraction of power is transmitted to ±1 diffraction orders in the *p* polarization rather than the *s* polarization, hence showing that such an effect is also polarization sensitive. Overall, the concept of a broadband spectral filtre with a narrow reflection is best suited for the *s* polarized input.

4. Experimental results

To prove the proposed theoretical concept, experimental fabrications are acquired. A fused silica (n = 1.47) trapezium profile grating was used as a substrate with the transverse period $\Lambda_x = 625$ nm and groove depth $h \approx 250$ nm. The conformal deposition of a high refractive index layer on the grating was performed by ion beam sputtering technology [25]. The main results are shown in Fig. 4.

The fabricated filter, shown in Fig. 4(a), consists of the 524 nm thickness Ta_2O_5 (n = 2.09 at 980 nm wavelength) thin film sputtered on the trapezium profile grating. The zeroth-order reflection profile is shown in Fig. 4(b), which is calculated by 2D RCWA of the structure shown in Fig. 4(a). The white circular part denotes the leaky mode reflection to be present, which is formed at $\lambda_c = \Lambda_x n_{sub} = 918.8$ nm. In such a case, the result is achieved even if the modulation form of thin film's surface does not perfectly repeat the modulation profile of the grating surface. Above the leaky mode regime, the transmission dips denote Fano resonances [4], which correspond to zeroth-order reflection. The cross-sections of transmission profiles are shown in Fig. 4(e, f). The agreement between the theoretical prediction and the experiment is best for the *p* polarization case where zeroth-order reflection and transmission dominate, which is for all wavelengths above λ_c in the transmission spectrum.

5. Conclusions

We have achieved triangular-like spectral reflection in the angle spectrum domain by optimization. The result is a narrow-angular filtre operating near the critical wavelength corresponding to the Rayleigh anomaly. It is also characterized by a high reflection coefficient in a relatively wide wavelength interval. So far, both effects have been perfectly achieved only by optimizing the geometrical parameters of the trapezium waveguide. Such photonic devices would be useful for both spectral and angular filtering, which can be applied in microlaser resonators for compactness [14, 26, 27].

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ERDVINIS IR SPEKTRINIS FILTRAVIMAS NAUDOJANT BANGOLAIDINIUS REZONANSUS

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Santrauka

Nanofotonika yra sparčiai besivystanti sritis, kurioje nagrinėjama šviesos sąveika su įvairiomis, tarp jų ir bangolaidinėmis, metamedžiagomis. Vienas ryškiausių pavyzdžių yra Fano rezonansu pasižymintys bangolaidiniai komforminiai plonasluoksniai filtrai, kurie gaminami ant periodinių paviršių gardelių pagrindo naudojant jonapluoščio dulkinimo (angl. *Ion Beam Sputtering*) technologiją. Šiais fotoniniais įtaisais galima atlikti erdvinio filtravimo funkciją pasiekus ištekančio (angl. *leaky*) modų režimo sąlygą. Jais galima naudotis kaip veidrodžiais, kurie siaurai atspindi kritusią šviesą kampinėje ir plačiai spektrinėje srityse. Šiame darbe buvo išspręstas optimizavimo uždavinys tobulinant trapecinės formos periodinį bangolaidį taip, kad būtų gautas aštrus plokščios viršūnės pavidalo atspindys kampiniame diapazone. Jo plotis spektre yra 46 nm. Siekiant įrodyti teorijos validumą, buvo atliktas tokių darinių gamybos eksperimentas ant trapecinės formos gardelių pagrindo.