Grating assisted rectangular integrated optical microresonators

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A wide, multimode segment of a dielectric optical waveguide, enclosed by Bragg reflectors and evanescently coupled to adjacent port waveguides, can constitute the cavity in an integrated optical microresonator. We outline a design strategy for these devices and give results of numerical simulations by means of mode expansion techniques, that exemplify the specific spectral response of the standing wave resonators.

Keywords: integrated optics, numerical modeling, optical microresonators, rectangular microcavities.

Introduction

Optical microresonators are at present discussed as basic elements for large scale integrated optics [1, 2], typically for applications in optical wavelength division multiplexing. The focus is on compact cylindrical disk- or ring shaped structures, designed for material systems with high refractive index contrast, where the technological implementation or the application itself usually requires a facility for post fabrication adjustment. If the tuning is to be realized by electrooptical means, a major obstacle may be encountered in the form of the strong anisotropy of some of the most promising electrooptic materials [3, 2]. The birefringence must be suspected to lead to a pronounced modulation, if not to leakage, of the circulating optical waves, i.e. to a lossy cavity.

These problems can be avoided in standing wave resonators, where the light propagation is restricted basically to one axis. Integrated optical microresonators with square or rectangular cavities have attracted attention only quite recently [4, 5, 6, 7]. In their conventional form, also these concepts have a severe technological disadvantage: An extremely high refractive index contrast is required for the total reflection effect at the facets of the waveguide segments [8] that serve as cavities; with the presently available materials a realization seems to be difficult.

A way out is found by replacing the waveguide facets by Bragg reflectors. This leads to a concept for a standing wave resonator in the form of a Fabry-Perot cavity with lateral, evanescent coupling. Fig. 1 sketches the structure and introduces the relevant parameters. While a parameterized time-domain coupled mode theory model is given in Ref. [4], so far apparently neither rigorous nor approximate simulations of these devices exist. This is what we would like to provide with this paper.

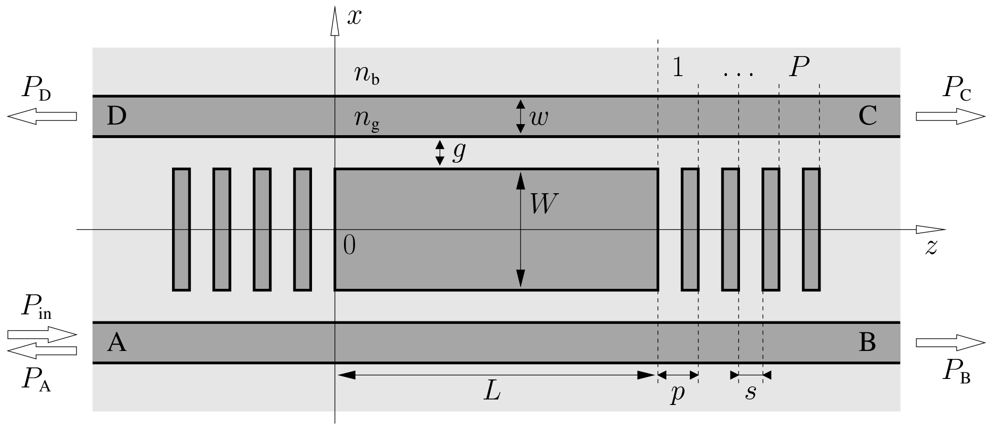

Fig. 1. Grating assisted rectangular resonator: Two parallel waveguide cores of width w are coupled by a cavity of width W and length L, separated by gaps g. Gratings with P periods of length p with a spacing s enclose the cavity. The guiding regions with refractive index n_g are embedded in a background medium with index n_b. Capital letters A to D denote the input and output ports.

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Design strategy

Assuming that the hypothetical device will be realized on the basis of rectangular Si_3N_4 cores (refractive index 1.98) surrounded by a SiO_2 background medium, we fix a common channel thickness of $0.223\,\mu$m. Then the values given in Table 1 correspond to the effective index projection of the realistic 3D structure, at a design wavelength of $\lambda_0 = 1.55\,\mu$m. For simplicity, all considerations are restricted to this 2D model and to TE polarization.

As a starting point of the resonator design we choose the width w of the port waveguides, such that these are single mode in a suitable wavelength region around λ_0; the values of Table 1 lead to an effective mode index $n_{\text{eff}} = 1.540$ at λ_0.

Reasoning along the coupled mode model of Ref. [6], only few (one or two) guided modes of the cavity segment are likely to be relevant for specific standing wave resonances. These modes are to be excited in the cavity; hence, to satisfy the phase matching condition, we adjust W such that the cavity waveguide supports a guided mode that is degenerate with the port fields. In the present case, W should be among the discrete values $(1.0 + j\,1.791)\,\mu$m, for integer j.

As a second condition, pronounced resonances require a reflectivity close to unity for the relevant modes at the ends of the cavity [6]. In contrast to an ordinary high contrast waveguide facet, where two cavity modes are necessary [8], with the present gratings a single cavity mode is sufficient. The corresponding Bragg reflectors can be constructed on the basis of a model of tilted plane wave incidence on a multilayer stack with equivalent refractive index composition. We consider an incidence angle θ that corresponds to the angle of the relevant mode in the cavity, defined by $\cos\theta = n_{\text{eff}}/n_{\text{g}}$. Optimization of the layer stack for the present mode angle of $15.69°$ at λ_0 leads to the grating parameters p and s as given in Table 1.

To select a suitable cavity width W, we computed single mode reflectivities for Bragg gratings according to the specification of Table 1 and Fig. 1, for $P = 5$ and $W = (1.0 + j\,1.791)\,\mu$m, in each case for incidence of the j-th order mode. Levels of 0.17, 0.21, 0.23, 0.24, 0.25, 0.26 were observed for $j = 0, 1, \ldots, 5$, with the last value already close to the limiting level of 0.28, the reflectivity of a plane wave, incident under an angle of $15.69°$ on a laterally unbounded equivalent multilayer stack. Obviously the reflectivity is the higher, the larger the fraction of the mode profile is that actually encounters the corrugation of the Bragg reflector. Therefore a width W corresponding to a higher order mode is preferred, (such that the phase matching condition is still sufficient to distinguish the cavity modes, the propagation constants of which become closer for large W). We set W to the value for order $j = 5$ for the present simulations. Fig. 2 shows that in this way indeed a suitable Bragg grating can be designed, with a spectral response that resembles the curve expected from the plane wave model surprisingly well.

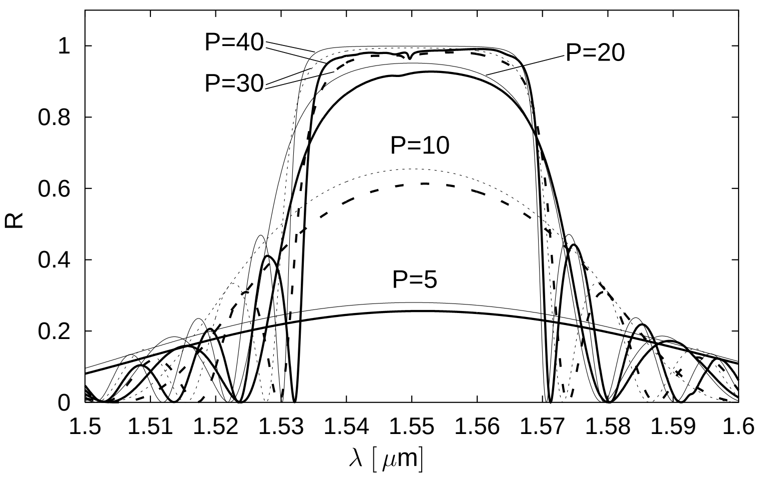

Fig. 2. Reflectivity R of Bragg-reflectors according to the specification of Table 1, versus the vacuum wavelength, for different numbers of grating periods P. The guided 5th order mode is launched in the wide cavity waveguide segment; the thick lines show the relative power levels that are reflected into that specific mode. The thin curves indicate the plane wave reflectivity of an equivalent multilayer stack for wave incidence under the respective mode angle ($15.69°$ at $\lambda = 1.55\,\mu$m).

Given the complex valued amplitude reflection coefficient $r \exp \mathrm{i}\varphi$ of the Bragg gratings, a resonance at λ_0 requires the total phase gain along one propagation cycle through the cavity to match an integer multiple of π. This amounts to a condition $L = (m\pi + \varphi)\lambda_0/(2\pi n_{\text{eff}})$ for the cavity length [6], with integer m. Neglecting the wavelength dependence of n_{eff} and assuming a long cavity $m\pi \gg \varphi$, one obtains $\Delta\lambda = \lambda_0/m = \lambda_0^2/(2Ln_{\text{eff}})$ for the spectral distance of two neighboring resonances. L, or m, respectively, is to be selected such that there is a chance for pronounced resonances in the window of high Bragg reflectivity around the design wavelength (m is about 119 and 159 in Fig. 3).

The gap width g is to be determined such that on the one hand there is a sufficient power transfer between the port waveguide and the cavity along the long unfolded light path in case of a resonance, while on the other hand the level of direct, unidirectional coupling (as in a conventional three-guide directional coupler, without a pronounced wavelength dependence) remains negligible. This parameter is selected finally on the basis of numerical experiments.

Numerical results

The design procedure leads to simulation parameters as listed in Table 1. The devices were simulated by means of the mode expansion techniques as described in Refs. [9, 5]; Fig. 3 shows the spectral response obtained in this way. We verified the results using an only recently released commercial simulation tool [10], based on bidirectional eigenmode propagation.

Table 1. Geometrical and material parameters for the simulations of Fig. 3. Including two Bragg reflectors and the cavity, the overall lengths of the devices are $182\,\mu$m and $203\,\mu$m.

n_g	n_b	$w/\,\mu$m	$g/\,\mu$m	$W/\,\mu$m	$L/\,\mu$m	$p/\,\mu$m	$s/\,\mu$m	P	$\lambda/\,\mu$m
1.60	1.45	1.000	1.600	9.955	59.860, 79.985	1.538	0.281	40	$\in [1.5, 1.6]$

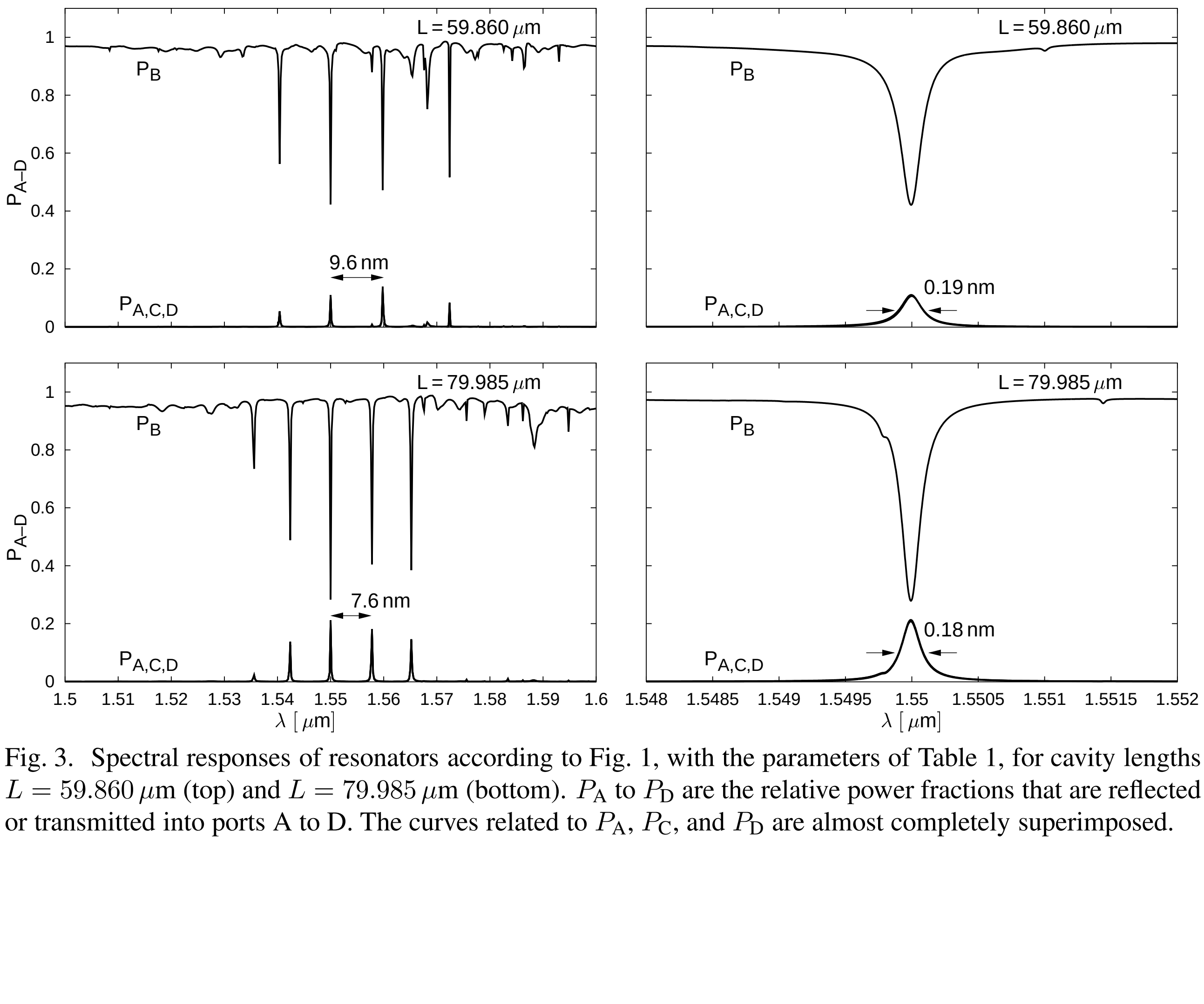

Fig. 3. Spectral responses of resonators according to Fig. 1, with the parameters of Table 1, for cavity lengths $L = 59.860\,\mu$m (top) and $L = 79.985\,\mu$m (bottom). P_{A} to P_{D} are the relative power fractions that are reflected or transmitted into ports A to D. The curves related to P_{A}, P_{C}, and P_{D} are almost completely superimposed.

The resonators are excited in port A by the right traveling guided mode of the lower core. For most wavelengths, the major part of the input power is directly transmitted to port B. Resonant states appear as a drop in P_{B} and a simultaneous increase of the reflected and dropped power fractions P_{A}, P_{C}, and P_{D}. As expected, the resonances are restricted to the range of high reflectivity of the Bragg gratings (cf. Fig. 2). The finesse for the two resonators is 51 (top) and 42 (bottom), here defined as the ratio between the free spectral range and the width at half maximum.

While at resonance the present device distributes the input among all four ports, a filter that properly drops the power into a single output channel can be realized with two cascaded single cavity resonators at a specific distance [4, 5]. The total length of the add-drop filter could be about $500\ \mu$m.

Remarks and conclusion

Based on quite simple design guidelines and moderate numerical means, the former results clearly demonstrate the working principle of the grating assisted rectangular microresonators, at least in terms of numerical simulations. We find the shape of resonances as predicted for high contrast standing wave resonators with finite waveguide segments as cavities, but in the present case with realistic material parameters, at the cost of an increased, but still acceptable length of the devices. Light propagation is oriented along a single axis; hence combination of this concept with an anisotropic electrooptic material for purposes of tuning poses no principal problems.

The design leaves plenty of room for further optimization. Apart from the theoretical limit of equal quarter transmission to all four ports at resonance, this concerns in particular the Bragg reflectors: Modifying the grating with the aim of a narrow, properly positioned bandgap should allow to restrict the spectral response to a single resonance. Alternatively, this could be achieved by means of two slightly different Bragg gratings at both ends of the cavity, adjusted such that their regions of high reflectivity overlap in only a narrow wavelength region. In principle, this should lead to devices with infinite free spectral range and finesse.

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[1] B. E. Little, S. T. Chu, W. Pan, and Y. Kokubun. Microring resonator arrays for VLSI photonics. *IEEE Photonics Technology Letters*, 12(3):323–325, 2000.

[2] Next-generation active integrated optic subsystems. Information society technologies programme of the European Commission, project IST-2000-28018, http://www.mesaplus.utwente.nl/nais/

[3] S. Follonier, M. Fierz, I. Biaggio, U. Meier, Ch. Bosshard, and P. Günter. Structural, optical, and electrical properties of the organic molecular crystal 4–N,N–dimethylamino–4'–n–methyl stilbazolium tosylate. *Journal of the Optical Society of America B*, 19:1990–1998, 2002.

[4] C. Manolatou, M. J. Khan, S. Fan, P. R. Villeneuve, H. A. Haus, and J. D. Joannopoulos. Coupling of modes analysis of resonant channel add-drop filters. *IEEE J. of Quant. Electr.*, 35(9):1322–1331, 1999.

[5] M. Lohmeyer. Mode expansion modeling of rectangular integrated optical microresonators. *Optical and Quantum Electronics*, 34(5):541–557, 2002.

[6] M. Hammer. Resonant coupling of dielectric optical waveguides via rectangular microcavities: The coupled guided mode perspective. *Optics communications*, 214(1–6):155–170, 2002.

[7] S. Kriswandhi. Simulation of a rectangular optical microresonator using bidirectional eigenmode propagation, 2002. C2V app. note A2002005, http://www.c2v.nl/software/support/appnotes/A2002005.pdf

[8] M. Hammer and E. van Groesen. Total multimode reflection at facets of planar high contrast optical waveguides. *Journal of Lightwave Technology*, 20(8):1549–1555, 2002.

[9] M. Lohmeyer and R. Stoffer. Integrated optical cross strip polarizer concept. *Optical and Quantum Electronics*, 33(4/5):413–431, 2001.

[10] OlympIOs Integrated Optics Software. C2V, P.O. Box 318, 7500 AH Enschede, The Netherlands; http://www.c2v.nl/software/