Experimental and Numerical Study of SiON Microresonators With Air and Polymer Cladding

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Abstract—A systematic experimental and numerical study of the device performance of waveguide-coupled SiON microresonators with air and polymer cladding is presented. Values of device parameters like propagation losses of the microresonator modes, the off-resonance insertion losses, and the straight waveguide to microresonator coupling are determined by applying a detailed fitting procedure to the experimental results and compared to results of detailed numerical simulations. By comparing the propagation losses of the fundamental TE polarized microresonator mode obtained by fitting to the measured spectra to the also experimentally determined propagation losses in the adjacent straight waveguide and the materials losses, it is possible to identify the loss mechanisms in the microresonator. By comparing experimental results for microresonators with air and polymethylmethacrylate cladding and a detailed numerical study, the influence of the cladding index on the bend losses is evaluated. It is demonstrated that the presence of an upper cladding can, under the right conditions, actually be beneficial for loss reduction.

Index Terms—Device modeling, integrated optics, loss measurements, microresonators, optical waveguides.

I. INTRODUCTION

CYLINDRICAL microresonators (MRs) have attracted considerable attention in the literature, as they are promising ultracompact building blocks for add-drop filters [1], [2], microlasers [3], all-optical switches [4], and sensing applications [5], and they open the route to a large area reduction of complex integrated optics devices [6]. They have been studied both theoretically [1], [7], [8] and experimentally [2]–[5], [9]–[15].

In the case of a waveguide-coupled cylindrical MR, it is well known (see, e.g., [1], [10], [14], and [15]) that one may describe the response in terms of the propagation losses of the MR-modes, the roundtrip phase shifts of the MR-modes, and the coupling between the MR- and straight waveguide (SW) modes.

The propagation losses of a MR-mode have been studied experimentally [10], [14], [15] and compared with a model for the scattering losses [15]. For system considerations, additional parameters like the off-resonance insertion loss are of primary importance, especially for applications where a large number of MRs are cascaded to perform complex functions [6], [16]. The coupling between an SW- and an MR-mode has been studied theoretically by means of coupled mode theory (CMT) based on [1], [7], but to our knowledge no comparison between the theory and experiments has been mentioned in the literature.

By choosing a certain coupled fraction between the SW- and MR-modes for given MR losses, one may optimize the shape of the transfer functions for the drop and through ports; however, the position of the resonance wavelengths (λ_{res}) is beyond control. An accurate definition of the resonance wavelength requires a high degree of control of the geometric parameters and the temperature; e.g., a SiON MR with radius of curvature $R = 25 \mu\text{m}$, $\lambda_{\text{res}} = 1.55 \mu\text{m}$, and $\Delta\lambda_{\text{res}} < 10 \text{ pm}$ typically requires a definition of $\Delta R < 2 \text{ nm}$ and a temperature stability within $\Delta T < 1^\circ\text{C}$ [14]. By use of a polymer overlay, a more or less temperature-insensitive MR has already been demonstrated [17], but a high degree of control of the geometric parameters or dedicated postprocessing techniques [18] are still required. Active (e.g., electrooptical [19], [20], thermo-optical [21], [22]) tuning of the resonance wavelength greatly relaxes the requirements for the control of the geometric parameters and the temperature [23], but in most cases also requires an upper cladding as platform for the electrodes.

The aims of this paper are as follows.

- 1) Compare the experimentally determined parameters like MR losses, coupling coefficients, and the finesse with the results of theory.
- 2) Identify the loss mechanisms of an MR-mode.
- 3) To study the influence of the index of an upper cladding on the losses and to give directions for the “best”-choice (in order to minimize the bend losses) for the cladding index.

This paper is organized as follows. In Section II, the experimental propagation losses and coupled fractions (of the fields) between the SW- and the MR-modes obtained by a detailed fitting procedure are discussed and compared with predictions based on theory and SW-measurements. Section III discusses the influence of an upper cladding and gives an explanation for the observed best choice for the cladding index. In the conclusion, directions for further optimization are given.

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II. COMPARISON BETWEEN EXPERIMENT AND THEORY

In this section, the experimentally obtained parameters of an MR with air cladding are compared with theory. Before discussing the experimental results, a summary of the device parameters is given; for more details, see [14].

A. Basic Characteristics of the Device

Fig. 1(a) gives a schematic view of the realized MR with the fabrication parameters. Light from the single-mode input SW is coupled to the MR. A second adjacent SW serves as add and drop channel. The symmetrically coupled MR supports two MR modes with a single vertical mode order. The calculated bend losses¹ [24], [25] ($\alpha_{\text{bend}} \sim 550 \text{ dB} \cdot \text{cm}^{-1}$) of the first radial order MR-mode ($q = \text{TE}(0, 1)$) are significantly higher than the calculated bend losses of the fundamental TE-polarized MR mode ($q = \text{TE}(0, 0)$), which increase monotonously with increasing wavelength, see Fig. 3(a). For efficient coupling between the TE(0,0) MR- and SW-modes, we designed single-mode SWs (effective index, $n_{\text{eff}} \sim 1.505$) with only a small phase-mismatch (see also [11]) with the TE(0,0) MR mode. Using CMT for one-dimensional (1-D) cross-sections [7], with the numerically calculated 1-D modal profiles [24], [25] of the SW- and MR-modes as input, we calculated the fraction of the field of the TE(0,0) SW mode ($|\kappa_{\text{TE}(0,0)}|$) coupled to the TE(0,0) MR-mode as a function of the gap and the wavelength.

An analytical model (see also [13] and [15]) for the power fractions (of the input) at the drop and through ports for an MR sustaining multiple MR-modes is introduced and discussed in the Appendix. It is shown that the power fractions at the drop and through ports for a symmetrically waveguide-coupled MR with no losses due to the coupling between the SW- and the MR-modes can be described in terms of the propagation losses (α_q) inside the MR, the coupled fraction² ($|\kappa_q|$) between the SW-mode and the MR-modes (q) and the roundtrip phase shift (ρ_q).

Based on the model in the Appendix and the calculated coupled fraction for a $0.75\text{-}\mu\text{m}$ gap ($|\kappa_{\text{TE}(0,0)}| \sim 17.9\%$) and bend losses ($2.4 \text{ dB} \cdot \text{cm}^{-1}$) for a wavelength of 1530 nm as input parameter, one finds—for the TE(0,0) MR-mode—a finesse (F) ~ 85 , a free spectral range (FSR) $\sim 8 \text{ nm}$, an at-resonance power extraction from the input port of $\eta_{\text{through}} \equiv P_{\text{in}}/P_{\text{through}} \sim 18.6 \text{ dB}$, and drop efficiency $\eta_{\text{drop}} \equiv P_{\text{drop}}/P_{\text{in}} \sim 78\%$. For an MR with a resonance wavelength on the ITU grid the adjacent channel (spaced at 0.8 nm or 100 GHz from the resonance wavelength) crosstalk (see [14]) is $\text{CT} \sim -18.5 \text{ dB}$.

B. Experiments Versus Theory

The MR devices (see Fig. 1) were structured in a low-pressure chemical vapor deposition (LPCVD) Si_3N_4 layer [26] on a thermally oxidized silicon wafer by standard optical lithography

¹Usually bend losses (i.e., the radiation losses due to the curvature) are expressed in $\text{dB}/90^\circ$ or $\text{dB}/360^\circ$. For the comparison of the calculated bend losses with scattering and materials losses, which are usually expressed in dB/cm , we prefer to express the bend losses in dB/cm .

²In the Appendix, it is shown—by using reciprocity arguments—that the coupled fraction from the SW- to the MR-modes is identical to the coupled fraction from the MR- to the SW-modes.

Fig. 1. (a) Schematic layout and cross-section (A-A) of the laterally waveguide-coupled microresonator. (b) SEM images of the realized laterally waveguide-coupled microresonator with designed gaps of $0.5 \mu\text{m}$ and (c) $0.75 \mu\text{m}$, respectively.

and reactive ion etching (RIE). Fig. 1(b) and (c) shows scanning electron microscope (SEM) images of realized microresonators with (designed) gaps of 0.5 and $0.75 \mu\text{m}$, respectively. Even though the gaps between the SW and the MR for devices with (designed) gaps of $0.5 \mu\text{m}$ are not completely open [see

Fig. 2. Measured spectral response (normalized to its maximum) at the through port for microresonators with (a), (b) air and (c), (d) PMMA cladding.

Fig. 1(b)] due to limitations in the photolithography process, they will be referred to as MR with 0.5- μm gaps throughout this paper. By measuring the scattered power from the SW (width $W_{\text{SW}} \sim 1 \mu\text{m}$) with an infrared (IR) camera as a function of the propagation length and the wavelength λ , we determined the propagation losses of the TE(0,0) SW mode [see Fig. 3(b)] to be³: $\alpha_{\text{SW}} \sim 7.0(0.2) - 7.9(0.1) \text{ dB} \cdot \text{cm}^{-1}$ in the wavelength region under consideration.

Symmetrically coupled MRs with gaps designed to be 0.5, 0.75, and 1 μm were characterized by coupling TE-polarized light of a tuneable laser diode (tuning range: 1480–1580 nm and linewidth $\Delta\nu < 100 \text{ kHz}$) into the input-SW and measuring the power in the through port (P_{through}). In the Appendix, it is shown that by fitting to the power in the through port as a function of the wavelength, parameters like the coupled fraction, propagation losses, and finesse can be obtained without the need of a reference measurement for the input power. Fig. 2(a) and (b) shows the spectral response at the through port (port 2) for 0.5- and 0.75- μm gaps (for MRs with a 1- μm gap, we could not observe minima in P_{through}). For a designed gap of 0.5 μm , we observed two periodic minima (FSR $\sim 8 \text{ nm}$) with finesse $F \sim 22$ and 2 due to the presence of the TE(0,0) and TE(0,1) MR modes, respectively. Increasing the gap to 0.75 μm practically removes the minima related to the TE(0,1) MR-mode and reduces the spectral width (finesse up to $F \sim 182$) and depth of the minima related to the TE(0,0) MR mode. The symmetry of the coupling between the MR and SW modes was checked by excitation of the MR via the add port and measuring the power in the drop port. By applying the fitting procedure described in the Appendix to the measured power in the through port, the fitted propagation losses and coupled fractions as a function of the wavelength and the gap could be obtained (see Figs. 3 and 4).

1) *Propagation Losses*: Fig. 3(a) shows the fitted propagation losses (fitted α_{MR}) of the TE(0,0) MR-mode as a function of wavelength. It appears that the fitted propagation losses of the TE(0,0) MR-mode increase with increasing wavelength. In general, the propagation losses of an MR-mode are composed of:

- 1) the bend losses of the MR-mode α_{bend} ;
- 2) the absorption losses of the materials α_{mat} ;
- 3) the surface roughness (e.g., of the etched sidewalls) induced scattering losses α_{sr} .

As a consequence, the propagation losses of the MR-modes can be expressed as

$$\alpha_{\text{MR}} = \alpha_{\text{bend}} + \alpha_{\text{mat}} + \alpha_{\text{sr}}. \quad (1)$$

From Fig. 3(a), it can be seen that the calculated bend losses of the TE(0,0) MR-mode increase monotonously with increasing wavelength for the wavelength range under consideration.

As one cannot distinguish between the surface-roughness-induced scattering and materials losses of the TE(0,0) MR-mode by, e.g., subtracting the bend losses from the fitted propagation losses, we studied—as an alternative—the propagation losses of the TE(0,0) SW-mode of the adjacent 1- μm -wide SW

$$\alpha_{\text{SW}} = \alpha_{\text{sr,SW}} + \alpha_{\text{mat,SW}} \quad (2)$$

with $\alpha_{\text{sr,SW}}$ and $\alpha_{\text{mat,SW}}$ defined as the surface-roughness-induced scattering losses and the absorption losses, respectively, of the TE(0,0) SW-mode. Fig. 3(b) shows that the measured propagation losses of the TE(0,0) SW-mode have a maximum $\alpha_{\text{SW}} \sim 7.9(0.1) \text{ dB/cm}$ for a wavelength of $\lambda = 1520 \text{ nm}$ and decrease to $\alpha_{\text{SW}} \sim 7.0(0.2) \text{ dB/cm}$ for a wavelength of $\lambda = 1580 \text{ nm}$. As the TE(0,0) SW-mode has a strong lateral confinement in the Si_3N_4 core layer (about 11% of the modal intensity in the air cladding), it is reasonable to approximate $\alpha_{\text{mat,SW}}$ by the propagation losses (α_{slab}) of the fundamental TE polarized mode of an $h_c = 300 \text{ nm}$ thick Si_3N_4 slab waveguide (about 6% of the modal intensity in the air cladding) on a thermally oxidized silicon wafer: $\alpha_{\text{mat,SW}} \sim \alpha_{\text{slab}}$. As a consequence, it follows from Fig. 3(b) that the absorption losses of the TE(0,0) SW-mode have a maximum $\alpha_{\text{mat,SW}} \sim 4.0(0.4) \text{ dB/cm}$ at a wavelength of $\lambda = 1520 \text{ nm}$ and decrease to $\alpha_{\text{mat,SW}} \sim 2.9(0.5) \text{ dB/cm}$ for a wavelength of $\lambda = 1580 \text{ nm}$. By subtracting the measured propagation losses of the TE(0,0) SW-mode from the measured absorption losses, it is possible to estimate the surface-roughness-induced scattering

³As a convention, the error in the measurements is indicated by a number between brackets.

Fig. 3. (a): Comparison between the fitted (α_{MR}) and estimated propagation losses (α_{est}) and the calculated bend losses (calculated α_{bend}) of the TE(0,0) MR-mode. (b) Comparison between the measured propagation losses (α_{sw}) of the TE(0,0) SW-mode and the propagation losses (α_{slab}) of the TE(0) mode of the $h_c = 300$ nm thick Si_3N_4 slab waveguide.

of the TE(0,0) SW-mode: $\alpha_{\text{sr,SW}} \sim 4(1)$ dB/cm for the wavelength range under consideration.

Even though the modal profiles of the fundamental TE-polarized SW- and MR-modes are different, and as a consequence the absorption losses and the surface-roughness-induced scattering losses (which are proportional to the fraction of the modal intensity at the etched interfaces [15]) of the SW- and MR-modes are in general different as well, they give (together with the bend losses) an indication of the propagation losses of the TE(0,0) MR-mode

$$\alpha_{\text{est}} = \alpha_{\text{bend}} + \alpha_{\text{sr,SW}} + \alpha_{\text{mat,SW}}. \quad (3)$$

From Fig. 3(a), it can be concluded that the thus obtained estimated propagation losses (estimated α_{est}) agree reasonably well with the fitted propagation losses (fitted α). As a consequence, the estimated (from the SW-measurements) surface-roughness-induced scattering losses and absorption losses of the SW-mode can be considered as reasonable approximations for the corresponding losses of the TE(0,0) MR-mode: $\alpha_{\text{sr,MR}} \sim 4(1)$ dB/cm and $\alpha_{\text{mat,SW}} \sim 2.9(0.5) - 4.0(0.4)$ dB/cm. Possible ways to reduce the propagation losses of the TE(0,0) MR-mode are as follows.

- 1) Annealing of the sample can reduce the hydrogen content of the (nonannealed) LPCVD Si_3N_4 layer, and as a consequence remove the maximum in the absorption losses around 1520 nm, but a floor in the absorption losses of $\alpha_{\text{mat,SW}} \sim 2.9(0.5)$ dB/cm is expected to remain.
- 2) Optimization of the reactive ion etching process in order to reduce the surface roughness at the etched sidewalls can in principle result in a decrease of the propagation losses of the TE(0,0) MR-mode by $\alpha_{\text{sr,MR}} \sim 4(1)$ dB/cm.

- 3) Increase the lateral contrast by etching deeper into (or through) the Si_3N_4 core layer and/or increase the thickness (h_c) of the Si_3N_4 core layer in order to reduce the bend losses or alternatively increasing the radius of curvature R . Both result in decreased bend losses, which account for $\alpha_{\text{bend}} \sim 1.2 - 6.3$ dB/cm of the propagation losses for wavelengths $\lambda = 1500 - 1580$ nm. It should be remarked, however, that etching deeper into the Si_3N_4 results in an increase of the sidewall area with large surface roughness and, as a consequence, can give rise to increased surface-roughness-induced scattering losses.

2) *Coupling Between Straight Waveguide and Microresonator:* Fig. 4 shows the fitted coupled fractions between the TE(0,0) SW- and MR-modes for gaps designed at 0.5 and 0.75 μm . For the MR with 0.75- μm gaps, the coupling increases with increasing wavelength, which is attributed to an increasing modal overlap between the MR- and SW-modes for increasing wavelength. In order to verify the CMT for 1-D cross-sections (as described in [7]), we compared the results obtained by this method with the fitted coupled fractions (see Fig. 4). For the MR with 0.75- μm gaps, the simulated coupled fractions have values within the same order of magnitude as the experimental ones but give an overestimation by a factor of three. Qualitative trends, like increasing coupling with increasing wavelength, are correctly predicted. For the MR with (designed) 0.5- μm gaps, there seems to be a much better agreement between the experiments and the simulations, but this is mainly attributed to the incomplete opening of the gaps that corresponds with an effectively smaller (than 0.5 μm) gap. It can therefore be concluded that the CMT for 1-D cross-sections as described in [7] is capable of giving the trends and the order of magnitude of the coupling for the above-discussed MRs.

3) *Off-Resonance Insertion Losses:* Low insertion losses for a cascade of MRs require that the power extracted from the input

Fig. 4. Comparison between the calculated (cal) and fitted (fit) coupled fractions between the TE(0,0) SW- and MR-modes as function of the wavelength and for gaps of 0.5 and 0.75 μm .

waveguide by a single MR in the off-resonance state (i.e., the off-resonance insertion loss $\alpha_{\text{ins,MR}}$)

$$\alpha_{\text{ins,MR}} \equiv -10 \cdot \log \left(\frac{P_{\text{through}}}{P_{\text{in}}} \right) \bigg|_{\lambda=\lambda_{\text{res}}+\frac{\text{FSR}}{2}} \quad (4)$$

is as small as possible $\{\lambda_{\text{res}}$: resonance wavelength of a single MR; P_{in} , P_{through} : power in the input and through port, respectively, at the reference plane (plane A-A in Fig. 1)}. In order to obtain P_{in} and P_{through} , two approaches can be discerned.

- 1) *Indirect approach*: The power in the through port at the reference plane is estimated by measuring the power in the input waveguide at the end facet of the sample and correcting for the propagation losses in the SW-section between the reference plane of the MR and the end facet. By estimating the power in the input waveguide at the input facet of the sample, which requires knowledge of the in-coupling efficiency, and correcting for the propagation losses in the SW-section between the input facet and the reference plane of the MR, it is possible to estimate the power in the input port at the reference plane.
- 2) *Direct approach*: Direct measurement of the power in the drop and through ports at the reference plane of the MR by, e.g., imaging of the scattering from the MR by an IR camera [27] or probing the evanescent field in a region around the reference plane with a photon scanning tunneling microscope [8], [11], [12].

We prefer the direct approach, as it allows determining the power in the input and through port at the reference plane without any need for corrections for the (often unknown) losses in the SW-sections and the in-coupling efficiency.

Fig. 5. IR-camera images (grayscale: black indicates low and white indicates high intensity) of the microresonator with a 0.75- μm gap to the adjacent straight waveguide for the on- and off-resonance state.

Fig. 5 shows IR-camera images (obtained by collecting the scattered light using an optical microscope) of the MR and the adjacent SWs for the on- and off-resonance case.

From Fig. 5, the difference between the intracavity intensity of the MR for the on- and off-resonance state can be clearly discerned. By imaging the MR and the adjacent SW by an IR camera as a function of the wavelength and using detailed image processing, we obtained the power in the input and through ports at the reference plane. Fig. 6(a) shows the thus-obtained fraction of the input power in the through port as a function of the wavelength. In a similar manner, we also obtained the averaged (over the area of the MR) intracavity power of the MR as a function of the wavelength; see Fig. 6(b). From Fig. 6(a) and (b), it can be seen that the minimum in $P_{\text{through}}/P_{\text{in}}$ coincides with the maximum of the integrated (over the microresonator area) intracavity power (P_{cav}). The full width at half maximum of the intracavity power (FWHM ~ 50 pm) agrees reasonably well with the FWHM obtained by fitting to Fig. 2(b) (FWHM ~ 60 pm).

From Fig. 6(a), we found a conservative estimate for the off-resonance insertion losses of the MR $\alpha_{\text{ins,MR}} < 0.15$ dB and an on-resonance power extraction from the input port $\eta_{\text{through}} \sim 1.25$ dB. Based on (A.5) in the Appendix and using the (in the preceding sections) fitted propagation losses and coupled fractions between the fundamental TE-polarized SW- and MR-modes, we estimated off-resonance insertion losses ($\alpha_{\text{ins,MR}} < 10^{-4}$ dB) considerably lower than observed experimentally. A possible explanation for the discrepancy between the estimated and observed off-resonance insertion losses of the MR can be found by taking into account the coupling between the TE(0,0) SW- mode and the TE(0,1) MR-mode (which has high propagation losses $\alpha_{\text{MR}} \sim 8.6$ dB/360°); for, e.g., a coupled fraction between the TE(0,0) SW- and the TE(0,1) MR-mode of $\kappa_{\text{TE(0,0)}} \sim 26.5\%$, we find off-resonance insertion losses of $\alpha_{\text{ins,MR}} \sim 0.15$ dB.

4) *Device Performance*: Using the fitted parameters presented in the previous sections, it is possible to discuss the device performance in more detail. As an example, the parameters for an MR with 0.75- μm gap and a wavelength of 1530 nm (with fitted parameters $|\kappa_{\text{TE(0,0)}}| \sim 6.6\%$, $\alpha \sim 12$ dB $\cdot$ cm $^{-1}$, FSR ~ 8 nm, and $F \sim 120$) are CT

Fig. 6. (a) Fraction of input power in through port and (b) intracavity power obtained by analysis of IR-camera images as a function of wavelength.

~ -21.5 dB, $\eta_{\text{through}} \sim 1.6$ dB, and $\eta_{\text{drop}} \sim 2.8\%$. The large difference between the calculated (see Section II-A) and observed device performance is attributed to the smaller (than calculated) coupled fractions between the TE(0,0) MR- and SW- modes and higher (than calculated) propagation losses due to the presence of surface-roughness-induced scattering losses and absorption losses. By allowing a somewhat larger adjacent channel crosstalk of, e.g., $\text{CT} \sim -14$ dB (i.e., $F \sim 51$), it is however possible to improve the device performance just by decreasing the gap between the SW and the MR: $|\kappa_{\text{TE}(0,0)}| \sim 20\%$, $\eta_{\text{through}} \sim 9.0$ dB, and $\eta_{\text{drop}} \sim 42\%$.

III. INFLUENCE OF AN UPPER CLADDING

For many applications, e.g., those involving driving electrodes, working with only an air cladding is not acceptable. In this section, therefore, the influence of an upper cladding on the device performance is studied experimentally and corroborated with detailed simulations. As an example system, we studied MRs identical to those discussed in the previous section, but now with a polymethylmethacrylate (PMMA) (index $n_{\text{cladding}} \sim 1.476$) instead of an air cladding.

A. Experiments on Microresonators With PMMA Cladding

Fig. 2(c) and (d) shows the spectral response for MRs with a PMMA cladding for gaps of 0.5 and 0.75 μm , respectively. Comparing the measured spectral responses for the MRs with PMMA and air cladding, one sees immediately that the presence of an PMMA upper cladding only slightly deteriorates the device performance. By applying (like in Section II) the fitting procedure described in the Appendix to the measured spectra in Fig. 2(c) and (d), we obtained the coupled fractions between the TE(0,0) MR- and SW-modes and the fitted propagation losses of

TABLE I
COMPARISON BETWEEN THE FITTED AND ESTIMATED PROPAGATION LOSSES (α , α_{est}), FITTED AND CALCULATED COUPLED FRACTION BETWEEN THE TE(0,0) MR- AND SW-MODES ($|\kappa|$, $|\kappa|_{\text{cal}}$) AND FITTED FINESSE (F) FOR AIR AND PMMA CLADDING, WITH $\lambda = 1530$ nm

	α [dB/cm]	α_{est} [dB/cm]	gap [μm]	F	$ \kappa $ [%]	$ \kappa _{\text{sim}}$ [%]
Air	12	10	0.5	22	27	34.0
			0.75	120	6.6	17.9
			1.0	---	---	9.4
PMMA	27	26	0.5	25	30	33.1
			0.75	61	10	17.4
			1.0	61	7	9.2

the TE(0,0) MR-mode. The results for wavelengths around $\lambda = 1530$ nm are summarized in Table I. From calculating the bend losses of the TE(0,0) MR-mode ($\alpha_{\text{bend}} \sim 5.6$ dB/cm for $\lambda = 1530$ nm) and determining the propagation losses of the TE(0,0) SW-mode of the adjacent SW ($\alpha_{\text{SW}} \sim 20.1(0.6)$ dB/cm for $\lambda = 1530$ nm), we obtained an estimate for the propagation losses of the TE(0,0) MR-mode (α_{est}). From Table I, it can be concluded that the estimated propagation losses of the TE(0,0) MR-mode agree reasonably well with the fitted propagation losses.

It appears that for the MR with PMMA cladding, the fitted propagation losses of the TE(0,0) MR-mode ($\alpha \sim 27$ dB/cm) are considerably higher than for the MR with air cladding ($\alpha \sim 12$ dB/cm). The high propagation losses of the TE(0,0) mode of the adjacent SW and the calculated bend losses ($\alpha_{\text{bend}} \sim 5.6$ dB $\cdot$ cm $^{-1}$) indicate that the increase in the propagation losses of the TE(0,0) MR-mode for an MR with PMMA cladding can be mainly attributed to an increase in the materials and/or the surface-roughness-induced scattering losses due to the presence of the PMMA cladding.

Table I also shows that the coupled fractions between the TE(0,0) MR- and SW-modes for the MR with PMMA cladding are somewhat larger than for the MR with air cladding (we now also observe an appreciable response for MRs with 1- μm gaps), which is attributed to the increased modal overlap between the MR- and the SW-modes due to the filling of the gap with PMMA. Even though the calculated coupled fractions (by CMT for 1-D cross-section, as described in [7]) for the MR with PMMA cladding are somewhat closer to the fitted values than for the MR with air cladding, it can be concluded that—like for the MR with air cladding—the CMT for 1-D cross-sections as described in [7] is capable of giving the trends and order of magnitude of the coupling between the SW- and MR-modes.

B. “Best” Choice for the Cladding Index

In the previous section, it was shown that MRs with a PMMA upper cladding have a response similar to the devices with an air cladding. In order to study the influence of the refractive index of the cladding (n_{cladding}) on the device performance in more detail, we calculated the bend losses as a function of the cladding index; see Fig. 7.

From Fig. 7, it can be concluded that upon increasing the index of the cladding (from $n_{\text{cladding}} \sim 1$), the bend losses decrease from $\alpha_{\text{bend}} \sim 2.4$ dB/cm toward a minimum of $\alpha_{\text{bend}} \sim 0.8$ dB/cm for $n_{\text{cladding}} \sim 1.3$ and increase rapidly for cladding

Fig. 7. Calculated bend losses of the TE(0,0) MR-mode as a function of the cladding index (wavelength, $\gamma = 1530$ nm); the vertical dashed line indicates the index of the SiO₂ buffer layer.

indexes larger than the thermal SiO₂ buffer layer ($n_{\text{cladding}} > 1.45$). These observations are somewhat counterintuitive, as one would expect the lateral contrast to decrease and, as a consequence, the bend losses to increase with increasing n_{cladding} .

In order to investigate the effect of an increasing index of the upper cladding on the bend losses in more detail, we analyzed the lateral contrast [28]

$$\Delta n_{\text{lat}} = \sqrt{n_{\text{eff,core}}^2 - n_{\text{eff,bg}}^2} \quad (5)$$

as a function of the cladding index. With $n_{\text{eff,core}}$ and $n_{\text{eff,bg}}$ as the core and background refractive indexes of an equivalent two-dimensional (2-D) structure (with the vertical dimension removed) obtained by, e.g., the effective index method (EIM) [27]. As for high index contrasts, the accuracy of the EIM is somewhat questionable. We calculated the lateral contrast by calculating the cutoff width ($W_{\text{TE}(0,1)}$) of the TE(0,1) SW-mode of the adjacent SW (but now with a variable width) by using a numerical mode solver for 2-D cross-sections [25] and applying the definition of the normalized frequency V as defined in [28]

$$V = \pi \Rightarrow \Delta n_{\text{lat}} = \sqrt{n_{\text{eff,core}}^2 - n_{\text{eff,bg}}^2} = \frac{\lambda}{2W_{\text{TE}(0,1)}}. \quad (6)$$

From a comparison between the curves of the bend losses and lateral contrast as a function of the cladding index, it follows that they are both antisymmetrical curves that increase (α_{bend}) or decrease (Δn_{lat}) rapidly for cladding indexes larger than the cladding indexes corresponding to the minimum α_{bend} , maximum Δn_{lat} , respectively. From Fig. 8, it follows that the maximum lateral contrast ($\Delta n_{\text{lat}} \sim 0.68$) occurs for a cladding index somewhat larger than the index of the (thermal SiO₂) buffer layer. The presence of a maximum in the lateral contrast can be explained by taking the derivative of the lateral contrast (5) with respect to the index of the cladding

$$\begin{aligned} \frac{\partial \Delta n_{\text{lat}}}{\partial n_{\text{cladding}}} &= \frac{S_{\text{core}} - S_{\text{bg}}}{2\Delta n_{\text{lat}}} \\ \text{with } S_{\text{core}} &\equiv \frac{\partial n_{\text{eff,core}}^2}{\partial n_{\text{cladding}}} \\ S_{\text{bg}} &\equiv \frac{\partial n_{\text{eff,bg}}^2}{\partial n_{\text{cladding}}}. \end{aligned} \quad (7)$$

Fig. 8. Calculated lateral contrast as a function of the cladding index.

Fig. 9. Calculated sensitivity of the squared core (S_{core}) (gray curves) and background indexes (S_{bg}) (black curve) of the equivalent 2-D structure as a function of the cladding index (n_{cladding}) and the thickness (h_c) of the core layer as parameter.

Fig. 9 shows the sensitivity of the squared core (S_{core}) and background (S_{bg} , with $h_c = 50$ nm) indexes of the equivalent 2-D structure for a change in the cladding index and the core thickness as parameters obtained by the EIM. From Fig. 9, it can be seen that $S_{\text{core}} > S_{\text{bg}}$ ($S_{\text{core}} < S_{\text{bg}}$) for an antisymmetrical layer stack with a cladding index smaller (larger) than the index of the buffer layer, indicating a maximum lateral contrast for a slightly antisymmetrical layer stack with only a single vertical mode (i.e., $h_c \leq 570$ nm). For increasing core thickness, the cladding index corresponding to a maximum lateral contrast (i.e., where $S_{\text{bg}} = S_{\text{core}}$) shifts to the left and the sensitivity S_{core} decreases monotonously, which indicates a smaller influence of the cladding index on the lateral contrast for increasing core thickness as a result of the better confinement of field in the core layer.

The TE(0,0) MR-mode has, however, a minimum in the bend losses for $n_{\text{cladding}} \sim 1.3$, in which case the lateral contrast ($\Delta n_{\text{lat}} \sim 0.51$) is considerably lower than the maximum. A qualitative explanation for the difference between the cladding indexes corresponding to a minimum in the bend losses and a maximum in the lateral contrast can be found by analyzing the Poynting vector in the transversal (i.e., orthogonal to the direction of propagation) direction ($\mathbf{S}_T$) for different cladding indexes; the total radiated power per unit area is proportional with $|\mathbf{S}_T|$.

Fig. 10. Contour plot of the magnitude ($|S_T|$) of the numerically calculated [25] transversal Poynting vector of the TE(0,0) MR-mode for different cladding indexes.

In the case of an air cladding, it can be seen from Fig. 10 that S_T —and consequently also the radiation loss due to the bending—is mainly directed into the buffer layer. Upon increasing the index of the cladding, the radiation gets increasingly directed into the cladding layer. If we assume, for the moment, that the modal intensity at the $\text{Si}_3\text{N}_4 - \text{SiO}_2$ interface is independent of the index of the cladding, it follows from the volume current method ([7]) that the contribution of the radiation into the buffer layer remains constant and, as a consequence, the change in the bend losses due to a change in the index of the cladding layer is directly proportional to the power radiated into the cladding layer. Using this argument, it can be understood (assuming constant lateral contrast) that the presence of an upper cladding creates an additional “loss channel” and results in an increase in the bend losses with increasing indexes of the cladding layer. As a consequence, the minimum in the bend losses will be shifted somewhat to the left of the maximum in the lateral contrast.

Fig. 11. Calculated surface-roughness-induced scattering losses of the 1- μm -wide straight waveguide in Fig. 1 normalized by the surface-roughness-induced scattering losses for a straight waveguide with air cladding as a function of the index of the cladding.

From the discussion above, it can be concluded that the “best” choice (with respect to low bend losses) for the index of the upper cladding is somewhat lower than the index of the buffer layer.

Absolute values for the surface-roughness-induced scattering losses can in principle be estimated from the surface roughness at the etched side walls (see, e.g., [15]). From the SEM images in Fig. 1(b) and (c), it was however not possible to estimate the surface roughness, due to the presence of a “white” border on the sides of the waveguides in the SEM images. The presence of this border is attributed to the accumulation of charges at the side walls [30]. By a combination of proper sample preparation and reducing the acceleration voltage, the charging effects can probably be reduced [30]. But this is outside the scope of this paper, where we are mainly interested in the influence of an upper cladding on the losses for a given structure. In order to estimate the effect of the cladding index on the surface roughness (at the etched sidewalls of the SW) induced scattering losses, consider the expression for the surface-roughness-induced scattering losses for a 2-D symmetrical waveguide given by [29]

$$\alpha_{\text{sr}} \propto (n_{\text{core}}^2 - n_{\text{cladding}}^2)^2 E_{\text{interface}}^2 \quad (8)$$

with core index n_{core} , cladding index n_{cladding} , and power normalized electrical field $E_{\text{interface}}$. Expression (8) can be generalized to the case of a three-dimensional SW, like in Fig. 1, by integration over the etched interfaces

$$\alpha_{\text{sr}}(n_{\text{cladding}}) \propto \int_{\text{interface}} d\ell (n_{\text{core}}^2 - n_{\text{cladding}}^2)^2 |\mathbf{E}_{\text{interface}}|^2. \quad (9)$$

Fig. 11 shows the calculated surface-roughness-induced scattering losses for the 1- μm -wide SW adjacent to the MR normalized by the calculated value for an SW with air cladding

$$\hat{\alpha}_{\text{sr,SW}}(n_{\text{cladding}}) = \frac{\alpha_{\text{sr,SW}}(n_{\text{cladding}})}{\alpha_{\text{sr,SW}}(n_{\text{cladding}} = 1)} \quad (10)$$

as a function of the cladding index. From Fig. 11, it follows that the surface-roughness-induced scattering losses for the SW decrease monotonously with increasing index of the cladding and are about 50% lower for cladding indexes somewhat lower than the index of the buffer layer. We therefore conclude that, apart from special cases like sensing applications [5], applying

an upper cladding with an index somewhat lower than the buffer layer instead of an air cladding is preferable, as it reduces both the bend losses and surface-roughness-induced scattering losses.

IV. CONCLUSION

It has been demonstrated that by applying a detailed fitting procedure to the measured power fraction (of the input power) at the through port as a function of the wavelength, it is possible to determine the propagation losses and coupled fractions between the modes of the microresonator and the adjacent straight waveguide. By combining the calculated bend losses ($\alpha_{\text{bend}} \sim 1.2 - 6.3$ dB/cm) with the measured propagation losses in the adjacent straight waveguide ($\alpha_{\text{SW}} \sim 7.0 - 7.9$ dB/cm), whose vertical dimensions are identical to the MR, a reasonable estimate for the propagation losses of the MR-modes can be obtained. By measuring the propagation losses of the modes in the straight (SW) and equivalent slab waveguides, the contributions of the materials losses ($\alpha_{\text{mat}} \sim 2.9 - 4.0$ dB/cm) and the surface-roughness-induced scattering losses ($\alpha_{\text{sr,MR}} \sim 4$ dB/cm) to the propagation losses can be estimated. From the wavelength dependence of the materials losses, it is expected that annealing of the LPCVD Si_3N_4 layer results in a decrease of the propagation losses with about 1 dB/cm. By improving the reactive ion etching of LPCVD Si_3N_4 layer, the propagation losses can be reduced by at most 4 dB/cm. In order to reduce the bend losses, increasing the radius of curvature is preferable, as increasing the lateral contrast (by, e.g., increasing the thickness of the Si_3N_4 layer) in general requires deeper etching into (or through) the Si_3N_4 layer and, as a consequence, is expected to result in increased surface roughness at the etched sidewalls.

A direct estimate for the off-resonance insertion losses for the MR with air cladding and $0.75\text{-}\mu\text{m}$ gaps has been obtained by imaging the MR and the adjacent SWs as a function of wavelength. The estimated off-resonance insertion losses of $\alpha_{\text{ins,MR}} < 0.15$ dB clearly shows that cascading of multiple MRs is feasible.

Based on a comparison between the fitted and calculated coupled fractions between the fundamental TE polarized SW- and MR- mode, it has been concluded that the 1-D coupled mode theory of [7] is well capable of giving a qualitative description (trends) and order of magnitude estimates of the coupling between SW and MR modes, but misses accuracy for a quantitative description. A possible route for improvement might be to extend the 1-D coupled mode theory to a coupled mode theory for 2-D cross-sections.

From detailed simulations and experiments, it has been shown that a cladding on top of the MR with an index lower than the SiO_2 buffer layer does not drastically increase the bend losses, and can actually minimize the bend losses, by taking an index of the cladding somewhat lower than the SiO_2 buffer layer. By detailed numerical analysis of the lateral contrast and the transversal Poynting vector, the minimum in the bend losses could be attributed to a maximum in the lateral contrast for an almost symmetrical layer stack and to the fact that the radiation pattern gets directed more into the cladding layer for increasing index of the cladding. Applying an upper cladding also reduces the surface-roughness-induced scattering losses and can be

Fig. 12. Schematic layout of a waveguide-coupled cylindrical microresonator and the corresponding four-port representation.

used as platform for, e.g., driving electrodes. Therefore, the use of an upper cladding is recommended.

APPENDIX ANALYTICAL MODEL

An analytical model of the response of a cylindrical microresonator in terms of the modal amplitudes of the straight waveguide and microresonator modes is presented (see also [31]). The aim of this Appendix is to demonstrate how parameters like the propagation losses and the coupled fraction between the SW- and the MR-modes can be obtained by fitting the analytical model to the experiments.

Consider the schematic layout of a waveguide-coupled cylindrical MR in Fig. 12. Throughout this Appendix, the following will be assumed.

- 1) The straight waveguide is monomodal and the MR-modes are propagating in the counterclockwise direction.
- 2) The evanescent field coupling between the MR- and SW-modes can be modeled as an abrupt process at the reference plane (i.e., dashed horizontal line in Fig. 12); this is a reasonable approximation, as the evanescent field coupling occurs in a small region around the plane of closest distance between the MR- and the SW-modes.
- 3) There is no coupling (mode conversion) between different MR-modes due to the presence of the adjacent straight waveguides.
- 4) There are no losses due to the coupling between the SW- and MR-modes.
- 5) There is no input signal at the add port.
- 6) The leaky MR modes can be approximated by quasi-guided modes, whose modal power can be normalized.
- 7) The CW fields have a time dependence $\exp(j\omega t)$, with ω as the angular frequency.

From reciprocity arguments [32], it can be shown that a symmetrical scattering matrix $M^{(m)}$ relates the modal amplitudes of the SW- and MR-modes at junction $(m+1)$ to the modal amplitudes at junction (m)

$$\begin{bmatrix} A^{(m+1)} \\ C^{(m+1)} \end{bmatrix} = \mathbf{M}^{(m)} \cdot \begin{bmatrix} A^{(m)} \\ C^{(m)} \end{bmatrix} \quad \text{with: } m = \{1, 3\} \quad (\text{A.1})$$

with $A^{(m)}$ defined as the modal amplitude of the SW-mode at junction m and $\mathbf{C}^{(m)}$ defined as a vector whose elements $C_q^{(m)}$ are the modal amplitudes of the MR-modes of order q . As we assumed no losses due to the coupling between the MR- and SW-modes, it is possible to simplify the scattering matrix M to

$$\mathbf{M}^{(m)} = \begin{bmatrix} t_0^{(m)} & -j\kappa_1^{(m)} & \cdots & -j\kappa_p^{(m)} \\ -j\kappa_1^{(m)} & \mu_1^{(m)} & 0 & 0 \\ \vdots & 0 & \ddots & 0 \\ -j\kappa_p^{(m)} & 0 & 0 & \mu_p^{(m)} \end{bmatrix}$$

$$t_0^{(m)} = \sqrt{1 - \sum_{q=1}^p |\kappa_q^{(m)}|^2}$$

$$\mu_q^{(m)} = \sqrt{1 - |\kappa_q^{(m)}|^2}$$

with: $q \in \{1, \dots, p\}$. (A.2)

From (A.2), it follows that the coupling between the MR- and SW-modes at junctions $m = 1, 3$ are denoted by the coupled fractions $(\kappa_q^{(1)}, \kappa_q^{(3)})$ between the SW-mode and the MR-modes of order q .

The propagation of the MR-modes can conveniently be described by the roundtrip phase shift ρ_q and the propagation losses α_q

$$C_q^{(m+1)} = t_q \cdot C_q^{(m+1)}$$

with

$$t_q = \sqrt{X_q^{(0)}} \cdot \exp\left(-j\frac{1}{2}\rho_q\right)$$

$$X_q^{(0)} = \exp(-\alpha_q 2\pi) \quad (\text{A.3})$$

with α_q defined as the propagation losses of the MR-mode of order q (in units [1/rad]) and $X_q^{(0)}$ defined as the fraction of the modal amplitude of the MR-mode of order q remaining in the MR after a single roundtrip for an unloaded (i.e., no coupling to the SW-modes) MR.

An explicit expression for the wavelength dependence of the roundtrip phase shift can be found by a first-order series expansion of the roundtrip phase shift around a central wavelength (λ_c) and identifying the periodicity (with wavelength) of the response with the free spectral range (FSR_q) of the MR-mode of order q

$$\rho_q = \rho_q(\lambda = \lambda_c) - \frac{2\pi}{\text{FSR}_q}(\lambda - \lambda_c). \quad (\text{A.4})$$

Combining (A.1)–(A.4) and assuming no input signal at the add port (i.e., $A^{(3)} = 0$), it is possible to express the modal amplitude at the through ($A^{(2)}$) port in terms of the modal amplitude at the input port ($A^{(1)}$); see also [8]

$$\frac{A^{(2)}}{A^{(1)}} = t_0^{(1)} - \sum_{q=1}^{\max} \frac{a_q}{b_q \exp(-jk_q(\lambda - \lambda_c)) - 1}$$

with

$$a_q = \frac{(\kappa_q^{(1)})^2}{\mu_q^{(1)}}; \quad b_q = \frac{\exp(j\rho_q)}{X_q} \Big|_{\lambda=\lambda_c}$$

$$X_q = \mu_q^{(1)}\mu_q^{(3)}X_q^{(0)}; \quad k_q = \frac{2\pi}{\text{FSR}_q}$$

and the modal amplitudes at the drop port ($A^{(4)}$) in terms of the modal amplitude at the input port ($A^{(1)}$)

$$\frac{A^{(4)}}{A^{(1)}} = - \sum_{q=1}^{\max} \frac{a'_q}{b_q \exp(-jk_q(\lambda - \lambda_c)) - 1} \quad (\text{A.6})$$

with

$$a'_q = \frac{\kappa_q^{(1)}\kappa_q^{(3)}}{\sqrt{\mu_q^{(1)}\mu_q^{(3)}}} \frac{\exp(j\frac{1}{2}\rho_q)}{\sqrt{X_q}} \Big|_{\lambda=\lambda_c}.$$

By fitting the absolute squares of (A.5) and (A.6) to the power fraction (of the input power) in the through and drop port, respectively, it is in principle possible to determine the following.

- 1) The fraction of the modal field remaining in the MR after a single roundtrip (X_q) and the finesse (F_q) [8] of the MR-mode of order q

$$|X_q| = |b_q|^{-1}$$

$$F_q = \frac{\pi}{2} \left\{ \arcsin \left(\frac{1 - |X_q|}{2\sqrt{|X_q|}} \right) \right\}^{-1}. \quad (\text{A.7})$$

- 2) The free spectral range of the MR-mode of order q

$$\text{FSR}_q = \frac{2\pi}{k_q}. \quad (\text{A.8})$$

- 3) The coupled fraction between the MR- and the SW-modes at junction $m = 1$

$$|\kappa_q^{(1)}|^2 = \frac{-|a_q|^2 + \sqrt{|a_q|^4 + 4|a_q|^2}}{2}. \quad (\text{A.9})$$

- 4) The coupled fraction between the MR- and the SW-modes at junction $m = 3$

$$|\kappa_q^{(3)}|^2 = \frac{-|\xi_q|^2 + \sqrt{|\xi_q|^4 + 4|\xi_q|^2}}{2}$$

with

$$\xi_q = \frac{|a'_q|^2}{|a_q|} X_q. \quad (\text{A.10})$$

- 5) The propagation losses of the MR-modes

$$2\pi\alpha_q = -\ln \left(\frac{|X_q|}{\sqrt{(1 - |\kappa_q^{(1)}|)(1 - |\kappa_q^{(3)}|)}} \right). \quad (\text{A.11})$$

In practice, it is more convenient to measure—instead of measuring the power at the junctions $m = 1, 2, 4$ —the power at

Fig. 13. Iterative procedure for determining the coupled fraction between the SW- and MR-modes at junction $m = 1$ by fitting (A.5) and (A.13) to the measured power in the through port.

the end facets of the input (P_{through}) and drop (P_{drop}) waveguide, which are proportional to the power fractions (of the input power) at junction $m = 2$ and $m = 4$, respectively

$$P_{\text{through}} = (\tau_{\text{through}})^2 \left| \frac{A^{(2)}}{A^{(1)}} \right|^2$$

$$P_{\text{drop}} = (\tau_{\text{drop}})^2 \left| \frac{A^{(4)}}{A^{(1)}} \right|^2. \quad (\text{A.12})$$

By fitting (A.12) to the absolute squares of (A.5) and (A.6), one finds alternative fitting parameters ($\tilde{t}_0^{(1)}$, $\tilde{a}'_q$, $\tilde{a}_q$, $\tilde{b}_q$) proportional to the original fitting parameters ($t_0^{(1)}$, a'_q , a_q , b_q)

$$\begin{aligned} \tilde{t}_0^{(1)} &= \tau_{\text{through}} t_0^{(1)} \\ \tilde{a}_q &= \tau_{\text{through}} a_q \\ \tilde{a}'_q &= \tau_{\text{drop}} a'_q \\ \tilde{b}_q &= b_q \\ \tilde{k}_q &= k_q. \end{aligned} \quad (\text{A.13})$$

From (A.13), it can be concluded that the fitting parameters b_q , k_q are independent of the scaling factors (τ_{through} , τ_{drop}); as a consequence the finesse (F_q) and free spectral range (FSR_q) can directly be determined from fitting to P_{through} or P_{drop} .

The coupled fraction between the MR- and SW-modes at junction $m = 1$ cannot be determined directly from fitting to P_{through} , P_{drop} . By imposing power conservation on the coupling between the MR- and SW-modes at junction $m = 1$, it follows that

$$t_0^{(1)} = \sqrt{1 - \sum_{q=1}^{\max} |\kappa_q^{(1)}|^2}. \quad (\text{A.14})$$

It is possible, as indicated in Fig. 13, to determine $t_0^{(1)}$ and $\kappa_q^{(1)}$ iteratively. As the modal amplitude at junction $m = 4$ [see (A.6)] is not related to $t_0^{(3)}$, the above-presented iterative procedure cannot be used for determining the coupling between the SW- and MR-modes at junction $m = 3$. As a consequence, the propagation losses of the MR-modes [see (A.11)] cannot be determined this way. In some specific cases, it is however possible to determine the propagation losses in an alternative way.

For an antisymmetrically waveguide-coupled (i.e., $\kappa_q^{(1)} \neq \kappa_q^{(3)}$) microresonator, $t_0^{(3)}$, $\kappa_q^{(3)}$ can be determined by excitation of the MR-modes via the add port (i.e., $A^{(3)} \neq 0$ and $A^{(1)} = 0$), imposing power conservation to junction $m = 3$ and applying an iterative-procedure similar to the one described in Fig. 13. By inserting the thus obtained $\kappa_q^{(3)}$ (and $\kappa_q^{(1)}$) into (A.11), it is possible to determine the propagation losses. In the case of a symmetrically waveguide-coupled (i.e., $\kappa_q^{(1)} = \kappa_q^{(3)} = \kappa_q$) microresonator, it is, however, possible to determine all the parameters (A.7)–(A.11) from a measurement of the power in the through port and excitation of the MR-mode via the input port

$$2\pi\alpha_q = -\ln \left(\frac{|X_q|}{(1 - |\kappa_q|)} \right). \quad (\text{A.15})$$

If necessary, a correction has to be made for the wavelength dependence of τ_{through} .

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