A Novel Polarization-Independent Wavelength-Division-Multiplexing Filter Based on Cylindrical Microresonators

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***Abstract*—A novel polarization-independent wavelength-division-multiplexing (WDM) filter, which exploits the strong polarization dependence of cylindrical microresonators by using them as wavelength-selective polarization splitters is presented. Detailed analysis of the polarization dependence of the filter shows that the filter is indeed virtually polarization-independent and has a wavelength response similar to the wavelength response of a microresonator coupled to two waveguides for a single polarization.**

***Index Terms*—Microresonators, optical waveguides, polarization diversity, wavelength-division multiplexing (WDM).**

I. INTRODUCTION

IN OPTICAL communication networks, standard single-mode fibers are used to transport information by optical means. In the fiber, the polarization state of the transported optical data is undefined. Therefore, polarization-independent behavior of the transported optical signal of integrated optics devices for telecommunication is of major importance for reliable operation. For ultracompact devices, like cylindrical micro resonators (MRs) [1]–[3], in high contrast technology it is well known that their response shows a strong polarization dependence (e.g., [3]). In literature, basically two approaches for reducing this polarization dependence can be discerned:

1) reducing the polarization dependence of the waveguides and basic building blocks (like directional couplers), [4]–[8];
2) by using polarization-diversity schemes or additional compensating functions (like a birefringence compensating film [8]), [8]–[11].

The advantage of the first approach is that the number of components (and chip area) remains practically unchanged, but it in general requires a higher degree of control of the layer parameters and the waveguide dimensions. As, besides polarization-insensitive behavior, other requirements have to be met simultaneously, the design becomes more complicated. Polarization-diversity schemes (in principle) allow for an optimization of the device performance independent of the minimization of the polarization dependence, but increase the number of components and consequently result in an increase of the chip area per device.

In this paper, a polarization-independent wavelength-division-multiplexing (WDM) filter is proposed that is based on a polarization-diversity scheme and exploits the strong polarization dependence of cylindrical microresonators. In Section II, the working principle of the proposed WDM filter is discussed. The performance and polarization dependence of the proposed filter are analyzed in Section III.

II. PRINCIPLE OF THE FILTER

Before discussing the proposed filter, it is instructive to discuss the implications of an unpredictable polarization state (i.e., both the amplitudes and their difference in phase of the mutually orthogonal polarization states are unknown) in the fiber for the response of an integrated optics wavelength filter.

Due to the birefringence (present in most optical waveguides), the TE and TM polarized modes in an optical waveguide system experience different optical path lengths (OPLs), resulting in a time delay between the mutually orthogonal polarization states at the output: polarization mode dispersion (PMD). In addition, due to their difference in effective index, the resonance wavelengths of a wavelength filter may be different for TE and TM polarized light: polarization-dependent resonance wavelength (PDW). Unwanted polarization conversion inside the wavelength filter allows for interference between the originally orthogonal TE- and TM-polarized light, which possibly have a difference in phase: polarization-dependent interference (PDI). The effects of PMD can be minimized by minimizing the OPL difference (from the input to the output) between the TE- and TM-polarized light. By—in addition—avoiding unwanted polarization conversions, the effect of PDI can be largely suppressed. Minimizing the effect of PDW on the filter performance requires matching of the resonance wavelengths (i.e., the effective indices) of the filter for TE and TM polarizations. For ultracompact devices in high-index-contrast technology, like cylindrical microresonators, the difference between the effective indices of the TE- and TM-polarized modes can be in excess of 0.01, and consequently PDW effects are difficult to avoid.

The filter proposed here (see Fig. 1) consists of: two functionally identical MRs (MR1, MR2), two functionally identical polarization converters (PC1, PC2), and functionally identical

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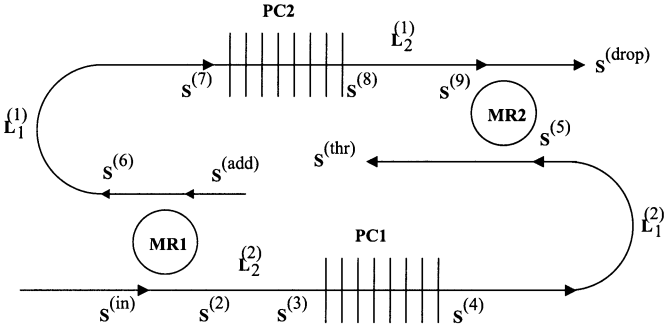

Fig. 1. Functional layout of the proposed polarization-independent filter. With $\mathbf{S}^{(q)}$ as the Jones vectors at ports q, see also (1).

straight waveguide sections ($L_2^{(1)} = L_2^{(2)} = L_2$) and curved waveguide sections ($L_1^{(1)} = L_1^{(2)} = L_1$). For this moment, we assume that the MRs are ideal wavelength-selective polarization splitters, which completely drop (e.g., port in → port 6) the TE-polarized light with wavelengths within the pass band, while all the TM-polarized light and TE-polarized light with wavelengths outside the passband remain in the input waveguide (e.g., port in → port 2). In addition, for this moment, we also assume complete polarization conversion by the polarization converters for all wavelengths.

First, consider wavelengths within the passband of the MRs. The TE-/TM-polarized component at the in port is transferred to port 6/2 and subsequently propagates through waveguide section $L_1^{(1)}/L_2^{(2)}$, respectively. All the TE-/TM-polarized light is converted to TM-/TE-polarized light at PC2/PC1 and subsequently propagates through waveguide section $L_2^{(1)}/L_1^{(2)}$. As the originally TE-/TM-polarized component has completely been converted to a TM-/TE-polarized component, it is transferred from port 9/5 to the drop-port. Because all the originally TE- and TM-polarized components remain mutually orthogonal while propagating through the filter, and both propagate through waveguide section L_1 as TE-polarized light and waveguide section L_2 as TM-polarized light, the effects of PMD and PDI are not present in the drop-port.

For wavelengths outside the passband of the MRs, all the light is transferred from the in-port to the through (thr) port. It should be remarked that, under the above-mentioned assumptions, the passband of the complete filter is only determined by the passband of the identical MRs (for TE polarization) and, as a consequence, no PDW effects are present for the proposed filter. However, the originally TE-/TM-polarized components at the in-port propagate through waveguide section L_2 as TE-/TM-polarized light and through waveguide section L_1 as TM-/TE-polarized light. As a consequence, the effects of PMD are present in the through port, unless waveguide sections L_1 and L_2 are functionally identical, i.e., they have identical transfer matrices.

III. Analysis of the Filter

In the previous section, it was shown that for the proposed filter—and under the above-mentioned assumptions—no effects of PMD, PDI, and PDW are present. In practice however, the MRs do not completely drop the TE-polarized light within the passband and also extract some of the TM-polarized light. In addition, the polarization converters have appreciable conversion efficiencies only for a limited wavelength range and the polarization conversion is in most cases not complete. Because the filter relies, besides on MR-based polarization splitters, on polarization converters with a strong polarization conversion within the passband of the MRs, it is important to have identical central wavelengths of the MRs and PCs and a bandwidth of the PCs significantly larger than the passband of the MRs. This choice is also illustrated in Fig. 2, which shows the typical drop efficiency (for TE-polarized light) of an MR and the polarization conversion of a PC with central wavelengths $\lambda_{\mathrm{MR}} = \lambda_{\mathrm{PC}} = 1.55\ \mu$m.

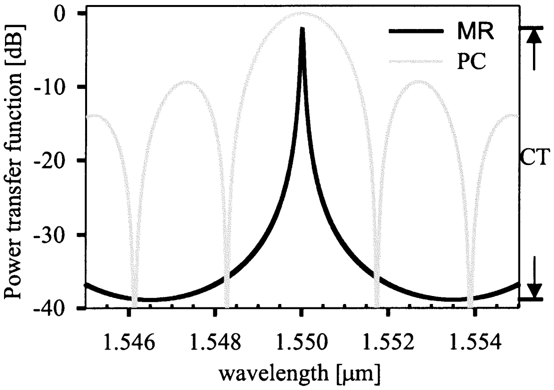

Fig. 2. Drop response of the MR (with crosstalk $CT < -37$ dB) and polarization conversion of the polarization converter as defined in Table I.

From Fig. 2, it also can be seen that the −3 dB bandwidth of the polarization converter ($\Delta\lambda_{\mathrm{PC}} = 1.6$ nm) is significantly larger than the −3 dB bandwidth of the MR ($\Delta\lambda_{\mathrm{MR}} = 0.06$ nm) and, as a consequence, the polarization conversion for wavelengths within the passband of the MR can be considered to be constant.

A more detailed discussion of the MR as a wavelength-selective polarization splitter will be given in Section III-A, followed by a summary of the most important characteristics of the polarization converters in Section III-B. In Section III-C, the polarization dependence of the complete tunable filter is analyzed in depth.

A. MRs as Wavelength-Selective Polarization Splitters

In [3], for example, it was shown that in some cases MRs only show an appreciable response (i.e., sufficient power dropped for wavelengths within the passband) for TE-polarized light, as the bend losses of the TM-polarized modes are simply too high.

Consider, for example, the micro ring with a Si_3N_4 core embedded in PECVD SiO_2 in Fig. 3. The micro ring is symmetrically coupled to the single-mode input and drop straight waveguides (SWs). For a central wavelength $\lambda_{\mathrm{MR}} = 1.55\ \mu$m, the (calculated[1]) bend losses of the fundamental TE-polarized MR mode ($\alpha_{\mathrm{bend}} \sim 3.5\cdot10^{-1}$ dB/cm) are significantly smaller than the bend losses for the fundamental TM-polarized MR mode

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[1] Calculated by using a commerially available finite-difference mode solver for both bends with one-dimensional and two-dimensional cross sections that are an integrated part of "Olympois" by C2V, Enschede, The Netherlands.

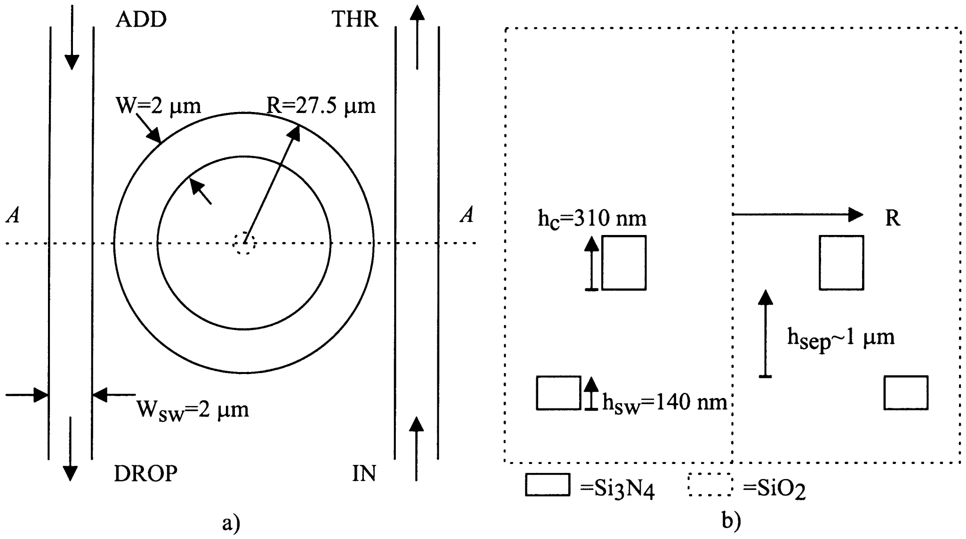

Fig. 3. (a) Layout and (b) cross section (*A*-*A*) of a vertically waveguide-coupled micro ring (MR) in SiON technology.

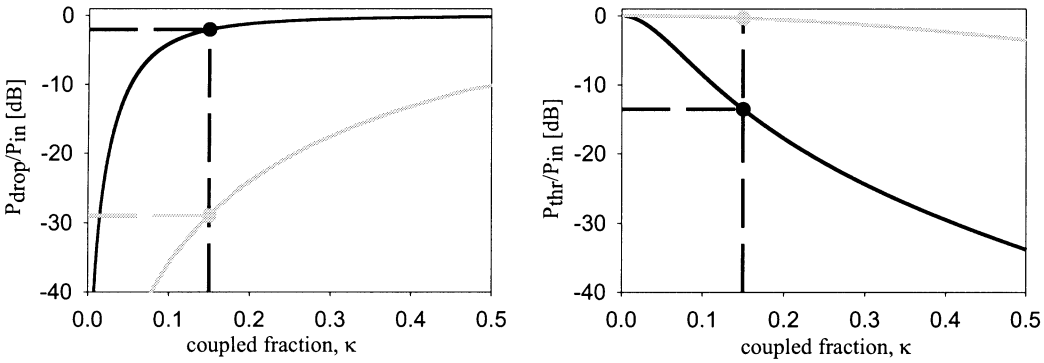

Fig. 4. Calculated power fractions (for the center wavelength $\lambda_{\mathrm{MR}} = 1.55$ μm) in the drop (left) and through (right) ports of the micro ring in Fig. 3, for TE (black line) and TM (gray line) polarizations as a function of the coupled fraction between the micro ring and the adjacent straight waveguides.

TABLE I
OVERVIEW OF THE PARAMETERS OF THE IDENTICAL RING RESONATORS (MR1, MR2) AND POLARIZATION CONVERTERS (PC1, PC2) USED IN THE ANALYSIS

Device	Parameter	Value	
		TE	TM
MR1,2	Coupled fraction, κ	0.15	0.15
	Propagation losses, α [dB/cm]	3.03	304
	Free Spectral Range, FSR [μm]	0.007	0.007
	central wavelength, λ_{MR} [μm]	1.55	---
PC1,2	-3 dB bandwidth, $\Delta\lambda_{\mathrm{PC}}$ [μm]	0.0016	0.0016
	Central wavelength, λ_{PC} [μm]	1.55	1.55

($\alpha_{\mathrm{bend}} \sim 301$ dB/cm) (see also Table I). By assuming scattering and materials losses of $\alpha_{\mathrm{SM}} \sim 3$ dB/cm for both polarizations, we find propagation losses of $\alpha \sim 3.35$ and 304 dB/cm for the TE- and TM-polarized MR modes, respectively. The calculated (by using a parametric model like in [12]) power fractions in the drop ($P_{\mathrm{drop}}/P_{\mathrm{in}}$) and through ports ($P_{\mathrm{thr}}/P_{\mathrm{in}}$) of the MR as a function of the coupled fraction κ (of the field) between the MR and the SW modes can be found in Fig. 4.

From Fig. 4, it can be concluded that the power dropped and extraction of power from the input port ($P_{\mathrm{in}}/P_{\mathrm{thr}}$) for TM polarization are significantly smaller than for TE polarization.

In the remainder of this paper, identical coupled fractions ($\kappa = 0.15$) for TE and TM polarization are assumed. Next, we analyze the on- and off- resonance behavior of the MR (also referred to as the ON- and OFF-states of the MR, respectively) in more detail. From Table II, it can be seen that the MR extracts 13.6 dB of the TE-polarized input, while virtually all the TM-polarized input is transferred to the through port. The MR is strongly polarization-selective, with suppression of the TM polarized in the drop port of -27 dB.

B. Asymmetrical Grating-Type Polarization Converter

Asymmetrical grating-type polarization converters, with a maximum polarization conversion $\varepsilon > 0.98$ (measurable maximum conversion efficiency was limited by the line width of the laser system), have been demonstrated in SiON technology [10], [13]. Based on [10], we designed a polarization converter with a length of 30 mm, a central wavelength of $\lambda_{\mathrm{PC}} = 1.55$ μm, and a -3-dB bandwidth of $\Delta\lambda_{\mathrm{PC}} = 0.0016$ μm; see also

TABLE II

OVERVIEW OF THE POWER TRANSFERRED TO THE ($P_{\mathrm{drop}}/P_{\mathrm{in}}$) AND THROUGH PORTS ($P_{\mathrm{thr}}/P_{\mathrm{in}}$) OF THE INDIVIDUAL MR FOR TE (MR-TE) AND TM (MR-TM) POLARIZATION AND THE COMPLETE FILTER FOR POLARIZATION CONVERSION EFFICIENCIES $\varepsilon = 0.98$, 1. WITH ON- AND OFF-STATES REFERRING TO WAVELENGTHS $\lambda = 1.55$ μm AND $\lambda = 1.5535$, 1.5465 μm, RESPECTIVELY.

	State	MR-TE	MR-TM	Filter (ε=1)	Filter (ε=0.98)
$P_{\mathrm{thr}}/P_{\mathrm{in}}$ [dB]	On	-13.6	$-3\cdot10^{-1}$	[-13.6,-12.8]	[-13.4,-11.3]
	Off	$-9\cdot10^{-4}$	$-3\cdot10^{-3}$	[$-7\cdot10^{-1}$,$-3\cdot10^{-3}$]	[$-7\cdot10^{-1}$,$-3\cdot10^{-3}$]
$P_{\mathrm{drop}}/P_{\mathrm{in}}$ [dB]	On	-2.0	-29	[-2.3,-2.0]	[-2.6,-1.9]
	Off	-39	-39	[-58,-23]	[-59,-23]
Finesse	---	109	5	---	---
CT [dB]	---	-37	-10	<-20.7	<-20.4

Table I. An interesting alternative might be the ultra compact MR-based polarization converter proposed in [14].

C. The Complete Filter

In this section, we analyze the polarization dependence of the complete filter, composed of identical MRs and PCs as described in Tables I and II. For proper working of the proposed filter, matching of the central wavelength of the MRs (for TE polarization) and the PCs is essential. In practice, the central wavelengths of the cylindrical MRs and PCs are difficult to control due to variations in the technology. By tuning the individual MRs and PCs, it is possible to match their central wavelengths. Thermally tunable ring resonators have been demonstrated in, among others, [15] and based on simulations and materials parameters we estimated a typical temperature sensitivity of $\delta\lambda_{\mathrm{MR}}/\delta T \sim 8$ pm $\cdot$ K^{-1} [3]. In [16], a relative temperature sensitivity of $(\delta\lambda_{\mathrm{PC}}/\delta T)/\lambda_{\mathrm{PC}} \sim 1.8 \cdot 10^{-4}$ K^{-1}—allowing for $\delta\lambda_{\mathrm{PC}} \sim 0.014$ μm for an induced temperature change of $\delta T \sim 50$ K—was demonstrated for a PC similar to the one presented here.

The polarization-dependent response of the complete filter can be described conveniently as a 4 × 4 matrix ($\mathbf{FM}$) relating the Jones vectors [17] at the through and drop ports [$\mathbf{S}^{(\mathrm{thr})}$, $\mathbf{S}^{(\mathrm{drop})}$] with the Jones vectors at the input and add ports ($\mathbf{S}^{(\mathrm{in})}$, $\mathbf{S}^{(\mathrm{add})}$)

$$\begin{bmatrix}\mathbf{S}^{(\mathrm{thr})}\\ \mathbf{S}^{(\mathrm{drop})}\end{bmatrix} = \mathbf{FM}\cdot\begin{bmatrix}\mathbf{S}^{(\mathrm{in})}\\ \mathbf{S}^{(\mathrm{add})}\end{bmatrix}$$

$$\text{Jones vector at port } q : \mathbf{S}^{(q)} = \begin{bmatrix}A^{(q)}\\ B^{(q)}\end{bmatrix}$$

$$\text{Power at port } q : P_q = |\mathbf{S}^{(q)}|^2$$

$$q = \{1,\ldots,9,\mathrm{in},\ldots,\mathrm{drop}\} \quad (1)$$

with $A^{(q)}$ and $B^{(q)}$ as the modal amplitudes at port q for TE and TM polarization.

For the analysis of the polarization dependence of the filter, we do the following.

1) Assume that the waveguide sections L1 and L2 have identical optical path lengths in order to minimize the effects of PMD (see Section II).
2) Assume functionally identical, thermally tunable (with respect to the resonance wavelength for TE polarized light) MRs described in Table I. In practice, thermal tuning does not allow simultaneous control of the central wavelengths of an MR for both polarizations. We therefore set the central wavelength for TE polarization by thermal tuning ($\lambda_{\mathrm{MR}} = 1.55$ μm) and consider the central wavelength for TM polarization as a free parameter.
3) Assume functionally identical, thermally tunable polarization converters whose central wavelengths are matched with λ_{MR}: $\lambda_{\mathrm{PC}} = 1.55$ μm.
4) Consider the power in the drop and through ports (as defined in (1)) as a function of the power at the in-port (P_{in}) only ($\mathbf{S}^{(\mathrm{add})} = \mathbf{0}$). Due to the symmetry of the filter, it can be shown that the response as a function of the power at the add port is related to the response as a function of power at the in-port: $P_{\mathrm{drop}}/P_{\mathrm{in}} = P_{\mathrm{thr}}/P_{\mathrm{add}}$ and $P_{\mathrm{thr}}/P_{\mathrm{in}} = P_{\mathrm{drop}}/P_{\mathrm{add}}$.

Under the above-mentioned assumptions and considerations and using (1), it follows that the powers dropped and transferred to the through port are a function of wavelength (λ), polarization conversion efficiency (ε), central wavelengths of MR1 and MR2 for TM polarization, and the polarization state (described by the ratio and the phase difference between the polarizations). We applied a worst case analysis that gives the maximum and minimum values for the power being dropped and transferred to the through port while taking into account all possible polarization states.

From Fig. 5 and Table II, it can be concluded that for polarization converters with $\varepsilon = 1$, the performance of the complete filter in the ON-state (i.e., the MRs are in the ON-state for TE polarization) is similar to the performance of a single MR in the ON-state for TE polarization. In the ON-state, the polarization dependence of the power dropped and transferred to the through port is 0.3 and 0.8 dB, respectively. In the OFF-state (i.e., the MRs are in the OFF-state for TE polarization), the power transferred to the through port has a polarization dependence of 0.7 dB, which is mainly attributed to the fact that for TM polarization and a MR in the ON-state (for TM polarized input) the extraction is nonzero: $P_{\mathrm{in}}/P_{\mathrm{thr}} \sim 0.3$ dB. From Table II, it can be concluded that the crosstalk in the drop port (as defined in [3]) between the ON- and the OFF-state increases from $CT \sim -37$ dB (for the single MR and TE-polarized input) to $CT < -20.7$ dB for the complete filter.

Fig. 6 shows the dependence of the filter response on incomplete conversion efficiencies of the polarization converters. From this figure, it can be concluded that for the OFF-state

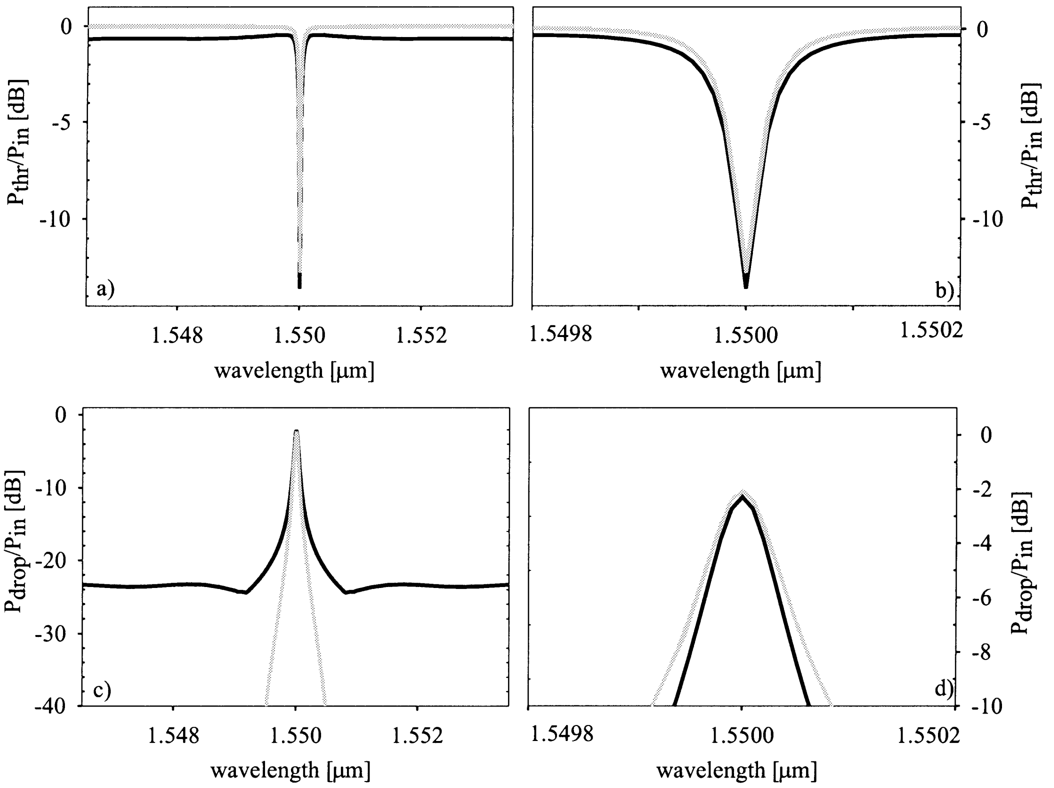

Fig. 5. Worst case analysis of (a), (b) the power transferred to the through port ($P_{\rm thr}/P_{\rm in}$) and (c), (d) dropped ($P_{\rm drop}/P_{\rm in}$) of the complete filter, with a polarization conversion efficiency $\varepsilon = 1$. The gray and black lines are the maxima and minima, respectively.

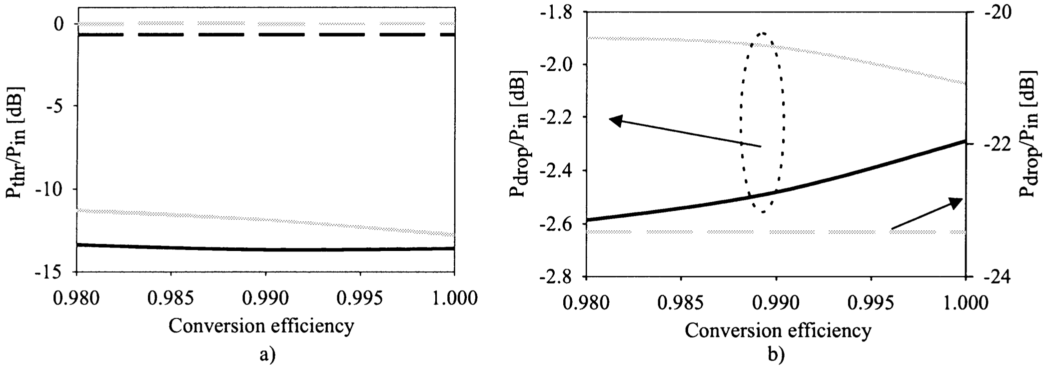

Fig. 6. Maximum (gray line) and minimum (black line) power fractions (of the input) transferred to the through port and dropped for a filter in the ON- (solid lines) and OFF-states (dashed lines). The curve for the minimum power fraction (of the input) dropped for a filter in the OFF-state, which varies between -59 dB and -58 dB, has been omitted.

the filter response is virtually independent of the conversion efficiency (ε) for the range of ε under consideration. For the ON-state, it can be seen from Table II that for $\varepsilon = 0.98$ the filter response depends somewhat more on the polarization state, but is still reasonably close to the response of a single MR for TE polarization.

IV. CONCLUSION

A polarization-independent filter based on strongly polarization-dependent cylindrical microresonators has been proposed and analyzed for its polarization dependence. The proposed filter has a small polarization dependence (only 0.7 dB for the power dropped for a filter in the ON-state and polarization converters with 98% conversion efficiency), is tolerant for small deviations from complete polarization conversion of the polarization converter, and shows a filter response similar to the TE-polarized filter response of an individual MR. It should be remarked that the presented filter type is not limited to stand-alone MRs, but can also be applied to cascades of strongly polarization-dependent MRs. Realization of the filter presented here in SiON technology is feasible.

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