CHAPTER 00

OPTICAL RESONATORS AND FILTERS

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Dielectric optical resonators of small size are considered for densely-integrated optical components. High-index-contrast microresonators of low Q are shown, using microwave design principles, to permit wavelength-sized, low-loss, reflectionless waveguide bends and low-crosstalk waveguide crossings. The analysis and synthesis of high-Q, high-order microring- and racetrack-resonator channel add/drop filters are reviewed, supplemented by simulation examples. Standing-wave, distributed Bragg resonator filters are also described. The study is unified by a coupled-mode theory approach. Rigorous numerical simulations are justified for the design of high-index-contrast optical “circuits”. Integrated-optical components are described within a polarization-diversity scheme that circumvents the inherent polarization dependence of high-index-contrast devices. Filters fabricated in academic and commercial research, and a review of microring resonator technology, advances and applications are presented.

1. Introduction

Integrated Optics has a long history [1,2], yet practical applications of integrated optics are still only a few. Optical components in current use are large compared with the wavelength, and this puts a limit on their density of integration. By using structures with a large refractive-index contrast one may reduce the structure size to the order of the optical wavelength. In this limit, the structures resemble microwave components that are on the order of a single wavelength in size.
Microwave components are shielded by metallic walls and do not radiate. At optical frequencies we do not possess materials with the properties of good conductors and hence radiation has to be kept in bounds by proper layout of the structures. Structures of high index contrast enable the designer to achieve radiation quality factors\(^a\) (Q’s) that are high compared with the overall (loaded) Q of the structure. The broader the bandwidth of the signals processed by the optical “circuits”, the lower is the required Q. Hence integrated optics will come into its own in the processing of signals at high bit-rates (25Gb/s and higher).

There is a downside to optical structures of low Q and large bandwidth: in order to obtain low Q, strong coupling between the resonator and the external “access” waveguides is required. This can be achieved by evanescent coupling across very narrow gaps, but narrow lithographically-defined gaps can be a fabrication challenge.

Coupled optical resonators can be the basis of wavelength filters with flat-top drop response characteristics that are desirable in telecommunications channel add/drop filter applications. The current state of the art allows for the fabrication, in a single lithographic step, of up to sixth-order (or six-coupled-cavity) resonator structures for 25GHz-bandwidth applications. In contrast, commercial thin-film filters for 25GHz applications are only available with performance of fourth-order resonators, and these require 200-250 dielectric layers to be sequentially deposited.

In this chapter, we discuss the issues arising in the design of integrated optical “circuits” using optical resonators. We also review experimental and commercial research into these structures. Microwave design principles are called upon for the tentative layout of structures of desired functionality [3,4]. High-index-contrast waveguides that support very small bending radii with acceptable radiation loss are key components serving as both the resonator cavities and the optical interconnects between various structures.

Two types of resonators will be discussed:

(a) Traveling-wave waveguide ring/racetrack resonators [2,5,6]
(b) Standing-wave Bragg-reflection resonators [7-10]

\(^a\) The quality factor (Q) of a resonator is defined as the ratio of the stored energy to the power flow out of the resonator due to various depletion mechanisms, times the angular resonance frequency. The Q measures the ability of a resonator to hold onto resonant energy.
Ring resonators support degenerate modes of traveling waves in opposite directions\(^b\). If the index contrast is high, the radii of the rings can be made small while maintaining low radiation loss, thereby providing a large free spectral range (FSR). Bragg-reflection resonators possess standing wave modes. Two standing wave resonators in cascade can simulate the performance of a traveling-wave resonator \(^{[11]}\). Radiation loss is an issue in both cases. In principle, one may greatly reduce the radiation loss of a Bragg resonator by proper choice of core and cladding indices \(^{[28]}\), but in practice the ideal situation can only be approximated.

Band-selective channel add/drop filters may be constructed using coupled resonators. The filter response is shaped by the disposition of the resonance frequencies of the coupled resonator system, and its coupling to the external waveguides. Mathematically, this leads to manipulation of the poles of the response function in the complex-frequency plane when engineering the drop-port response. In the sections that follow, various add/drop filter designs using ring and Bragg-reflection resonators are presented. The filter response is modeled using coupled-mode theory \(^{[5,10-12,26]}\). Numerical finite-difference time-domain (FDTD) simulations performed on the structures are shown to be consistent with this model. The FDTD simulations, take radiation losses into account and thus serve as a check as to the adequacy of the resonator design.

High-index-contrast waveguides possess considerable structural birefringence\(^c\). Hence the response of the optical circuits is typically polarization-dependent. Since fiber communication applications require polarization independence, the device response must be made polarization-insensitive. A polarization-insensitive response can be achieved by separating the two polarizations of the incoming signal and rotating one so that both polarizations are processed in identical structures. At the output, one of the polarizations is rotated again and the two are recombined. This calls for a broadband polarization splitter-rotator. Several integrated polarization converters have been proposed \(^{[13-16]}\). In Section 6, we describe a combined polarization splitter-rotator \(^{[17]}\).

The cross-section of high-index-contrast waveguides is small and efficient coupling to fibers presents challenges. Approaches have been published in the literature \(^{[30,31]}\). We present one design based on these proposals.

\(^b\) when free-running, in the absence of coupling structures. Coupled external waveguides or resonators may split the degeneracy of the two standing-wave modes of a ring causing coupling between the two traveling waves. In practice, for weak coupling this is a small effect.

\(^c\) due to the cross-sectional waveguide shape, as contrasted against birefringence of material origin.
2. Microwave Circuits and Optical “Circuits”

In the heyday of radar development, it was common to simulate the transmission responses of well-known electrical circuits with sequences of microwave waveguide components. This approach enabled the designer to use circuit theory and standard tables to construct apparatus with the desired response. “Microwave Circuit Design” using components of size comparable to a wavelength gave way to MMICs (monolithic microwave integrated circuits), where all microwave components are made small compared to a wavelength and only the transmission lines interconnecting them retain dimensions comparable to a wavelength.

Optical components cannot be shrunk to sizes small compared to a wavelength because metallic conductors do not perform as good conductors in the optical regime. This fact promises a longer time-span for the concepts of “microwave circuit design” applied to integrated optics. The absence of an optical conductor also implies that optical components have to rely on dielectric discontinuities to provide wave guidance. If the effect of radiation loss is to be kept small, the radiation Q must be kept high compared with the loaded Q of the device. For a resonant frequency \( \omega_0 \), the radiation Q \( (Q_r) \) is defined as \( \omega_0 \) times the energy \( W \) divided by the power lost to radiation. The external Q \( (Q_e) \), is \( \omega_0 W \) divided by the power coupled into output waveguides. The loaded Q \( (Q_L) \) is related to the other Q’s by

\[
\frac{1}{Q_L} = \frac{1}{Q_r} + \frac{1}{Q_e}
\]

The loaded Q in turn determines the processing bandwidth of the structure. For large bandwidths, the loaded Q is reduced and radiation losses pose less severe limitations. With the advent of 20 and 40 Gb/s bit-rates, the bandwidths have become sufficiently large that structures can be realized that do not suffer excessively from radiation losses.

Integrated optical circuits call for dielectric waveguide interconnects. These imply bends and crossings of waveguides. Bends have inherent radiation loss. Using structures of high index contrast, it is possible to design bends within an area of a few square wavelengths. The structures resemble microwave components and hence one can expect that the expertise gained in microwave circuit design can also be used to address problems in integrated optics design. We first apply resonator theory to the design of simple, compact waveguide bends and crossings, and then follow this with an in-depth study of resonator-based filters.
3. High-Transmission-Cavity-Waveguide (HTC-WG) Design

A lossless microwave resonator coupled to the outside by two waveguides, both with equal coupling (or external Q’s), transmits from one waveguide to the other without reflection at the resonance frequency of the resonator. Figure 1(a) shows the schematic representation of such a two-port system. Increased coupling
between the resonator and the outside enlarges the bandwidth of reflection-free transmission. The reflection $R$ and transmission $T$ at resonance are:

$$R = \left( \frac{Q_e}{2Q_o} \right)^2 \left( \frac{Q_e}{1 + \frac{Q_e}{2Q_o}} \right)$$  \hspace{1cm} (3.1)$$

$$T = \frac{1}{\left( 1 + \frac{Q_e}{2Q_o} \right)^2}$$  \hspace{1cm} (3.2)

This principle can be used to make reflection-free bends in waveguides. It can be extended to optics with the caveat that an optical resonator radiates unless special precautions are taken. Figure 1(c) shows the field in the two-dimensional, TE model of a right-angle bend constructed by “brute force”, that is, with no special precautions. An FDTD simulation, where the color code is for field amplitude, shows that the performance of the bend is very poor, as expected. The transmission is only of the order of 35%, the reflection is 20% and the rest is radiation. Figure 1(d) shows a dielectric “resonator” coupled to two dielectric waveguides at an angle of 90°. The resonator has a 45° reflector which aids the mode-matching from input to output. Hence, the design is based on microwave-circuit and ray-optics considerations. The transmission is 98%, while the reflection is -40dB [4,18]. The performance is indeed gratifying. It is one example of microwave circuit ideas applied to integrated optics.

High-index-contrast waveguides have widths of the order of one half-wavelength in the medium of the guide, whereas waveguides of low index contrast have widths much larger than a half wavelength. Simple perpendicular crossings of low index contrast waveguides can be easily realized without excessive cross-talk, because the field traveling in one waveguide goes through many reversals within the opening into the crossing waveguides. Thus, the overlap integral to evaluate the excitation of the perpendicular mode is small, and that mode is not excited. This is not true in the case of waveguides of high index contrast. Here, again, the resonator design principle can be invoked as shown in Fig. 2(a-c). The resonant modes must be anti-symmetric with respect to the symmetry plane cutting the crossing waveguides [19]. To minimize reflection, mismatch of the incident wave is removed by grooves of proper width and spacing, which serve like the matching “irises” in metallic resonators. Fig. 2(d-e)
shows the field patterns from simulations of two-dimensional, proof-of-concept models of different crossings, and Fig. 2(f) illustrates their performance [4,18].

In addition to transmission resonators, microwave design principles have been applied to show that wavelength-sized, square dielectric microcavities coupled to waveguides can be used to achieve wavelength-selective channel add/drop filter functionality [11,4].
4. Add/Drop Ring- and Racetrack-Resonator Filters

Microring and racetrack resonators permit high Q, along with the benefits of a traveling-wave resonator. The latter include simple control of the resonant mode spectrum and the inherent separation of all ports of interest in add/drop filter configurations. As a result, they occupy a prominent position in current research.

Figure 3 shows a simulation of the 2D model of a simple channel-dropping filter using a racetrack resonator coupled to two waveguides. A signal traveling upward in the guide on the left is coupled to a traveling-wave resonance of the racetrack and transferred to the other guide within the resonance bandwidth of the resonator. A racetrack may be preferable to a circular ring since the coupling region between the resonator and waveguides is longer, the spacing between waveguides is larger, and hence less strict fabrication tolerances are present. On the other hand, the modal mismatch at the straight-to-bent section interfaces must be addressed – otherwise the loss may be excessive. This can be done by using waveguide offsets or, in principle, the resonator concept introduced in Section 3. In our example of Fig. 3, the bend radius in the racetrack resonator is gradually varied from infinite (straight) to a minimum value and back to suppress junction loss and reflection due to modal mismatch, while maintaining a short cavity.

An alternative approach for increasing the coupling gap involves retaining the low-loss circular ring resonator and wrapping the bus waveguide around the resonator in order to increase the coupling length and thus permit a larger gap. In
this case, care must be taken to phase-match the coupler and keep the bend loss in the bus waveguide within acceptable bounds.

4.1 Analysis by Coupled Mode Theory

FDTD simulations in Figure 3 fully account for radiation loss. If this loss is known or estimated by some means, the performance of the filter can also be modeled by simple coupled mode theory, the results of which are shown as solid lines in the Fig. 3(b). As the physics of the filter are well captured by coupled-mode theory, we now review the coupled mode equations.

Denote by $U$ the amplitude of the resonator mode excited in the racetrack (see Fig. 4(a)). The amplitude is normalized so that $|U|^2$ is equal to the mode energy. The racetrack mode couples to two waveguides, ($\alpha$) and ($\beta$), and obeys the equation [5,10]

$$\frac{dU}{dt} = (j\omega_o - \frac{1}{\tau_{ca}} - \frac{1}{\tau_{cb}} - \frac{1}{\tau_o})U + \sqrt{\frac{2}{\tau_{ca}}} a_1 + \sqrt{\frac{2}{\tau_{cb}}} a_4 \tag{4.1}$$

where $a_1$ and $a_4$ are the incident waves in the two waveguides, normalized so that $|a_1|^2$ and $|a_4|^2$ are equal to the incident power in the two waveguides; $1/\tau_{ca}$ and $1/\tau_{cb}$ are the coupling rates; and $1/\tau_o$ is the decay rate due to the loss (radiation and other losses combined). The resonant mode $U$ couples back into the outgoing waves in the waveguides in the clockwise direction:

$$b_2 = a_1 - \sqrt{\frac{2}{\tau_{ca}}} U \tag{4.2}$$
The coupling equations are derived under the slowly-varying envelope approximation and the coefficients are adjusted to obey energy conservation in the absence of resonator loss. The phase of $U$ is chosen conveniently so that all coefficients are real. Note that the “backward” waves $b_j$ and $b_4$ remain unexcited if the resonant mode is a pure traveling wave. Perturbations to an ideal traveling-wave resonator may cause the actual modes to become hybrid [20]. The presence of the bus waveguides alone can, in the case of strong coupling, split the degeneracy of the standing-wave modes of a ring resonator significantly, and thus result in coupling between the traveling wave modes [72,73]. In some cases the degeneracy may be restored by proper positioning of the two bus waveguides.

Equations (4.1)-(4.3) are used, with $\alpha_4 = 0$, to evaluate the performance of the add/drop filter of Figure 3. As can be seen, the form of solution of the coupled-mode equations shown in solid curves is capable of reproducing very effectively the FDTD simulation results indicated by points. The drop-port transfer characteristic of a single racetrack resonator filter is Lorentzian. For responses with flatter passbands and steeper roll-off, a cascade of coupled resonators is needed. Such a cascade is illustrated in Fig. 4(b). If the number of coupled resonators is odd, the transfer is from $a_1$ to $b_3$, whereas for an even number of resonators the transfer is from $a_1$ to $b_4$. Here, we summarize the coupled mode equations for the case of an odd number, $N$, of resonators, and excited solely by $a_1$. For the first resonator, $n = 1$, we have

$$\frac{dU_1}{dt} = (j\omega_1 - \frac{1}{\tau_{ea}} - \frac{1}{\tau_{ao}})U_1 + j\kappa_{12}U_2 + \sqrt{\frac{2}{\tau_{ea}}}a_1.$$ (4.4)

The resonators $1 < n < N$ obey the equation

$$\frac{dU_n}{dt} = (j\omega_n - \frac{1}{\tau_{en}})U_n + j\kappa_{n,n-1}U_{n-1} + j\kappa_{n,n+1}U_{n+1}$$ (4.5)

and the last resonator satisfies

$$\frac{dU_N}{dt} = (j\omega_N - \frac{1}{\tau_{en}} - \frac{1}{\tau_{oN}})U_N + j\kappa_{N,N-1}U_{N-1}.$$ (4.6)

The coefficients of coupling between resonators obey the relation

$$\kappa_{n,n-1} = \kappa_{n-1,n}^*$$ (4.7)
Figure 5. Third-order racetrack resonator filter, 2D-model: (a) TE electric field from FDTD simulation excited by a short pulse, and (b) the resulting drop- and through-port spectral responses. A fit of the FDTD results using the coupled-mode theory model of the filter is also shown.

Figure 6. Bandpass filter circuit constructed from a cascade of series and parallel resonant circuits: (a) ladder network form, and (b) equivalent form with identical resonators spaced by quarter-wave impedance inverters. The case with four resonators is shown. Mapping the coupled-mode model of high-order resonator optical filters to these circuit models allows known circuit theory to be used in synthesis of responses [7,12,5].
imposed by energy conservation, under the assumption of bound uncoupled modes. The equations for the coupling to the waveguides are now:

\[ b_2 = a_1 - \frac{2}{\tau_{ea}} U_1 \]  \hspace{1cm} (4.8)

\[ b_1 = -\frac{2}{\tau_{e\beta}} U_N \]  \hspace{1cm} (4.9)

These equations may be solved to yield the transfer from guide \((\alpha)\) to guide \((\beta)\), and correspondingly the remaining signal in \((\alpha)\). The solution for the latter, the “reflection” coefficient (or through-port response), is of simpler form and is expressed in terms of a continued fraction [5]:

\[ \frac{b_2}{a_1} = 1 - \frac{2}{\tau_{ea}} \frac{1}{j(\omega - \omega_1) + \frac{|\kappa_{12}|^2}{|\kappa_{23}|^2} + \frac{|\kappa_{N-1,N}|^2}{|\kappa_{N-1}|^2} + \frac{1}{\tau_{e\beta}}} \]  \hspace{1cm} (4.10)

Here, the resonators are assumed lossless \((1/\tau_{ea} = 0)\), or else their loss decay rates may be thought of as having been absorbed into the imaginary part of complex resonator-frequency variables \(\omega_n\). The transfer (drop-port) response has a more complex form (see, e.g., [12]) but, for lossless resonators, obeys power conservation with (4.10). The drop-port response is all-pole, and can be shown to share its pole locations with the reflection response (4.10).

These equations are used to analyze the filter structure based on three coupled resonators in Figure 5. Fig. 5(a) shows a field snapshot from an FDTD simulation. A pulse of finite length is launched into the simulation window which leads to the uneven appearance of the excitation in the three racetrack resonators in the snapshot. This results from the simultaneous excitation of multiple longitudinal modes of the resonators. That is, the broadband spectrum of the pulse spans several FSRs of the resonators. Since the bandwidth of the excitation is wide, the computation yields information on the transfer function over a wide spectrum, part of which is shown in Fig. 5(b) (circles).

A fit of the simulation results using the presented coupled-mode theory model, with the constraint (4.7), is overlaid in solid line. A better fit is possible if
constraint (4.7) is relaxed to $\kappa_{n,n+1} = \kappa_{n-1,n}$. The latter condition results when the theory is derived for leaky (rather than bound) uncoupled resonator modes. This variant of coupled-mode theory is used in Sec 4.3 for the example of Fig. 8.

To account for the asymmetry in the response, the model fit requires unequal resonance frequencies even though the resonators in Fig. 5(a) are identical. This effect is due to self-coupling, expanded on in Sec. 4.3 [78].

### 4.2 Synthesis of Filter Responses

Equation (4.10) is also the standard form for the reflection coefficient of a ladder cascade of series and parallel resonant circuits, in the narrowband approximation, as shown in Figure 6(a). The conversion from series to parallel circuit can be accomplished by insertion of quarter-wave lines (e.g. [74]). Hence, the circuit of Fig. 6(a) is also represented by parallel resonant circuits connected across the two wires, with quarter-wave sections of transmission line between them (Fig. 6(b)). Here, the resonators are all identical and the structure starts to resemble the coupled rings of Figure 5. The role of the quarter-wave lines is played by the phase shift of 90 degrees contained in the coupling coefficients that are all multiplied by (the imaginary unit) j.

The circuits of Figure 6 were studied in the 1940’s and 1950’s, and tables were compiled for the choice of parameters so as to produce optimal band-selective filter response characteristics [21]. For the widely-used Butterworth (maximally flat passband) and Chebyshev (equi-ripple passband) designs, simple explicit formulas also exist [5, 75, 74]. Thus the coupling of modes-in-time model comes useful in both analysis and synthesis of filters.

### 4.3 Design and Numerical Simulation

While two-dimensional device models (e.g. Figs. 3,5) suffice to explain the physics of microring and racetrack filters, particularly in high index contrast structures three-dimensional simulations are necessary for reliable design.

Microring radiation losses may be evaluated by numerically solving for the leaky propagating mode of the ring’s constituent bent waveguide, or by directly solving for the complex-frequency leaky resonant mode of the resonator [76,72]. In the latter case, the radiation $Q$ is given by the ratio of the real and imaginary parts of the complex frequency, $Q \equiv -\omega_r / 2\omega_l$. High-index-contrast resonators necessitate consideration of the full-vector field. For an example ring resonator of

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\[d\] It is also the standard form, exactly, of the reflection response of an LC low-pass ladder network.
4μm radius, Fig. 7(a) shows the radial electric field component of the fundamental leaky resonance near 1545nm, over the ring cross-section. Fig. 7(b) shows the dependence of bending loss and radiation Q on radius at 1545nm. The radiation Q is relevant for radii which establish a resonance near 1545nm.

The coupled-mode theory model presented in the previous section to analyze microring filters has been advanced on the merits of the physical intuition it provides. The parameters of the model were found in Figs. 3, 5 by fitting the response obtained from FDTD simulation. However, when derived rigorously from Maxwell’s equations [77], coupling of modes-in-time directly provides the coupling coefficients through overlap integrals defined within the theory. The latter are not unique and depend on the chosen basis. A formulation over a magnetic-field basis of two uncoupled leaky resonator modes is used to study the coupling of two microrings of the kind shown in Fig. 7, here with an 8μm radius. Fig. 8(a) shows the coupling for various spacings between the two ring resonators as calculated ab-initio by coupled-mode theory, and as obtained from 3D FDTD simulations. The computed coupling, in the form of frequency splitting $2\sqrt{\kappa_{12}\kappa_{21}}$, that is natural to coupling of modes-in-time is converted (as in [5]) to a fractional power coupled across the shared directional coupler that is more familiar in the context of traveling-wave resonators. Comparison to the FDTD result shows agreement.

Figure 7. Vector-field 3D numerical modeling of the bending loss and associated radiation Q of high-index-contrast microring resonators (800×400 nm core, 100nm overetch, other dimensions in plot): (a) radial (dominant) electric-field component of the fundamental TE-like resonant mode near 1545nm, for 4.04 μm outer ring radius. Square-root field is shown to highlight radiation. The finite-difference numerical method employs perfectly-matched-layer (PML) boundary conditions to the right and bottom of the computation window to absorb outgoing radiation and properly model radiation loss of the resonance [72]. (b) Bend propagation loss and radiation Q vs. ring radius.
However, coupled-mode theory yields less accurate predictions as the index contrast or coupling is increased (seen in Fig. 8(a)). Most importantly, it is not practical for the prediction of changes in radiation loss due to resonator coupling (i.e., coupling to radiation modes) that can be important in high-index-contrast resonator design. Thus, 3D numerical simulations are essential for reliable high-index-contrast design. Fig. 8(b) shows the out-of-plane magnetic field from a 3D FDTD simulation of ring-ring coupling for Fig. 8(a). Relevance of the coupled-mode model advanced in Section 4.1 is extended by using coefficients computed from rigorous numerical simulations. An alternative model relevant only to traveling-wave resonators uses transfer matrices and waveguide modes [58].

Finally, optimal cascaded-resonator filter responses (Sec. 4.2) are synthesized using identical resonant frequencies. An important effect to be accounted in high-index-contrast filter design is the coupling-induced frequency shift (CIFS) in resonators, which causes identical resonators to acquire slightly different resonance frequencies when coupled [78]. This frequency shift may be evaluated numerically by considering the phase shift in propagation along one microring due to the index perturbation of its neighboring structures. The coupling of modes-in-time formalism can, in principle, account for such frequency shifts with the insertion of diagonal self-coupling terms, $\kappa_{n,n}$, into Eqns. (4.4)-(4.6). These terms can be absorbed into a net resonant frequency and reveal that the solution...
to restoring “pre-coupling degeneracy” is to predistort the uncoupled resonator frequencies such that they become identical in the coupled configuration.

4.4 Fabricated High-Order Microring Filters

Thin-film filters and microring resonators both benefit from coupled cavity arrangements. Whereas the realization of high-order thin-film filters relies on the sequential deposition of up to three hundred dielectric layers, high-order ring cavities are fabricated all at once in a single deposition and etch step.
Examples of fabricated coupled microring resonators are shown in Figure 9. This figure shows scanning electron micrographs of first-, second-, and sixth-order cavities using rings as small as 20 μm in radius, and were fabricated by Little Optics, Inc. The refractive index contrast in these examples was 17% [22]. Figure 10 compares the responses from fabricated filters of order one to six, and eleven. In this figure the filter bandwidths have been normalized to their respective 3dB bandwidths in order to compare and contrast filter shapes and out-of-band signal rejection. Clearly, higher-order filters give superior response, as they are intended to. Filters with linewidths ranging from 1 GHz to 100 GHz have been realized, and are suitable for many applications as is highlighted in Section 7.

5. Distributed Feedback Resonators with Quarter-Wave Shift

A uniform Distributed Feedback (DFB) structure coupled to an input and output waveguide acts as a filter that passes electromagnetic radiation at its resonance frequencies lying outside the stop-band, and reflects radiation within its stop-band. A quarter-wave shift introduced at the center of the structure produces a high-Q resonance at the center-frequency of the stop-band and the structure permits full transmission at this frequency [23]. The response is Lorentzian. Coupled quarter-wave shifted resonators can be used to construct filters with desired responses in a way similar to the filter design with ring resonators.

A quarter-wave grating resonator filter is shown in Figure 12(a) [79,80]. We denote the amplitude of the electric field in the forward wave by $a$, and in the backward direction by $b$. They are normalized so that the net power in the waveguide is

$$\langle P_z \rangle = |a|^2 - |b|^2.$$  \hspace{1cm} (5.1)

We write the forward and backward waves

$$a(z) = A(z) \exp(-\pi z / \Lambda)$$ \hspace{1cm} (5.2)

$$b(z) = B(z) \exp(\pi z / \Lambda)$$ \hspace{1cm} (5.3)

where $\Lambda$ is the grating period. The coupled mode equations for the grating are

$$\frac{dA}{dz} = -j\delta A + j\kappa B$$ \hspace{1cm} (5.4)

$$\frac{dB}{dz} = j\delta B + j\kappa A$$ \hspace{1cm} (5.5)
where $\delta \equiv \beta - 2\pi / \Lambda$ is the detuning from the Bragg wavelength $\Lambda$. With $\kappa$ real and positive, the phase of the waves is referenced to the position of the peak of the dielectric grating, where the periodic refractive-index perturbation, $\Delta \varepsilon(x, y, z)$, is a maximum. At resonance, $\delta = 0$, and the solution is

$$A(z) = A_+ \exp(-\kappa z) + A_- \exp(\kappa z)$$  \hspace{1cm} (5.6)$$

$$B(z) = -j [A_+ \exp(-\kappa z) - A_- \exp(\kappa z)]$$  \hspace{1cm} (5.7)$$

The phase of the E-field does not appear explicitly in (5.4) and (5.5) since the spatial dependence $\exp(\pm j\beta z)$ of the carrier has been factored out. However, it can be shown that the standing wave of the E-field under the exponential envelope has a maximum that is displaced by $1/8$th of a wavelength from the peak of the grating corrugation, as shown in Figure 11(a). The removal of a quarter-
wave section at \( z = 0 \) in the pattern of Figure 11(a) can match the field solutions decaying in opposite directions. The addition of a quarter wave section can match the patterns if one of the patterns is reversed in sign (phase shifted by \( \pi \)). In either case a resonant mode is created. This trapped resonance is coupled to the incoming and outgoing waveguides if the two gratings are of finite length. When excited from one end, full transmission occurs at resonance. The transmission response is Lorentzian.

Higher-order filters can be constructed by cascading such resonators. A fourth-order filter can be constructed as shown in Figure 11(b). It is formed of five gratings with four quarter-wave gaps. The equivalent circuit is that of Figure 6(b). The quarter-wave shift required between resonators as shown in Figure 6(b) is accomplished automatically by continuing without a break the output grating reflector of one resonator into the input grating reflector of its neighbor. The reason for this is the \( 1/8\lambda \) displacement of the standing wave pattern from the peak of the grating corrugation. The grating length chooses the equivalent value of \( Z_o^2C_r/L_i \) whereas the product \( L_iC_r \) is set by the resonance frequency \([24-27]\).

The performance of a four-channel Reconfigurable Optical Add/Drop Multiplexer (ROADM) that is commercially available from Clarendon Photonics is shown in Figure 12(b). The channel spacing is 100GHz, passband widths are 50GHz, and the out-of-band rejection (crosstalk) is \(-30\)dB. The filter’s polarization dependent wavelength (PDW) variation is low with the center frequency of the filters differing by less than 10GHz for the two polarizations. The fiber-to-fiber insertion loss is 4dB. It is surmised that each filter incorporates four resonators (this hypothesis is suggested by the four “wiggles” in the drop spectra at \(-30\)dB). The grating lengths are chosen to produce a Chebyshev bandpass transmission response.

Periodic slow-wave structures do not radiate if they are infinitely long. A finite structure with a quarter-wave shift radiates at the transitions from the
uniform waveguides to the periodic structure and at the quarter-wave shift. In
principle, this radiation can be suppressed in a two-dimensional slab or
cylindrical DFB structure through the use of four different indices as shown in
Figure 13 [28]. The indices are so chosen that transverse E-field patterns are
identical within every segment of the TE mode in the slab case, and of the \( TE_{0n} \)
mode in the cylindrical case. In both cases this requires

\[
\tilde{n}_1^2 - \tilde{n}_2^2 = n_1^2 - n_2^2
\]

where \( n_1 \) and \( n_2 \) are the core and cladding indices of one layer, respectively, and
their tilde-denoted counterparts are those of the next.

6. Polarization Splitter-Rotator and Fiber-Chip Coupler

High-index-contrast structures permit smaller bends and smaller structures.
However, it is difficult to make high-index-contrast structures polarization
insensitive. Fiber-optic systems cannot permit polarization sensitivity since
propagation along fibers causes a continuously changing polarization. We
propose to achieve polarization insensitivity by splitting the incoming
polarizations, rotating one of them and then processing both polarizations in
parallel in two identical structures. After passage through the structures, the two
polarizations are recombined. Phase delays need not be identical if a second
polarization transformation is permitted. Figure 14 shows a schematic of such a
scheme [17]. The symmetry of the approach inhibits polarization dependent loss.

Several proposals for integrated optic polarization splitters and rotators have
been published [13-16]. However, with the exception of the polarization splitter
offered by [16], all such proposals rely on mode coupling to achieve the desired
result. As a result of modal (waveguide) dispersion, approaches based on mode
coupling tend to be wavelength-sensitive. Moreover, in order for modes to
couple efficiently, the modes must be phase-matched and waveguides precisely spaced leading to strict fabrication tolerances.

Recently, integrated polarization splitters and rotators have been proposed that rely only on adiabatic following and therefore do not suffer from these limitations [29]. The approach works on the premise that a mode will follow and evolve along a perturbed structure so long as the coupling to other modes introduced by the perturbation is sufficiently small to allow the modes to dephase before substantial power exchange occurs. The polarization splitter and rotator are presented in Figures 15 and 16, respectively, along with results of three-dimensional FDTD simulations.
The polarization splitter begins from a cross-shaped waveguide with degenerate polarization states and gradually shifts the two arms of the cross apart. Although the TE-like and TM-like modes of this structure are phase-matched, coupling between them is prevented by mode symmetry and the TE-like and TM-like modes follow the horizontal and vertical waveguides, respectively. The polarization rotator mates up to either of the output arms of the polarization splitter depending on whether a TE or TM on-chip polarization is desired, and is essentially an approximation of a twisted waveguide. The upper and lower layers are progressively moved outward into the evanescent field of the mode while core material is added to the middle layer. The results of the FDTD simulations indicate that near perfect splitting and rotating of polarizations is achieved across the entire 1.45 μm to 1.65 μm band in structures only 50 μm long.

Finally, the task of coupling from a fiber to a single-mode high index contrast waveguide with the cross-shaped cross-section discussed above needs to be addressed. The mode diameter of the fiber mode is on the order of 8-10 microns, whereas that of a typical high-index-contrast waveguide is between a few tenths of a micron in size in Silicon and 1-2 microns in more moderate “high index contrast”. Here again, adiabatic tapers are of great utility, as attested to by the many such proposed solutions [30,31]. Figure 17(a) shows a tapered transition to the cross waveguide proposed by Dr. G. Gorni. The wide middle layer tapers down to a small 200x250 nm cross-section with a mode distribution that approximates that of the fiber. The remaining 50-micron-long section of the taper introduces a top and bottom waveguide and transitions to the cross-shaped
waveguide used as the input to the polarization splitter/rotator component. The performance characteristics of this taper are shown in Figure 17(b).

7. Review of Microring Resonator Technologies

The previous six sections have addressed the physics and design of integrated optical structures using traveling- and standing-wave microresonators. Of them, in recent years the microring resonator has attracted a considerable amount of attention among researchers, fueled by telecommunications applications. It has been responsible for a large body of research advances. In this and the following section, we review advances in microring resonator technology and the emerging applications for microrings.

Although microring resonators for wavelength filters have been proposed as far back as 1969 [2], fabrication technology did not evolve sufficiently for the realistic realization of sub-100 micron structures until about the earlier 1990’s. There are two fundamental challenges in realizing high-Q ring resonators. The first is finding a high index contrast material system in which low loss waveguides can be fabricated. The second is the ability to pattern very narrow gaps that are essential to the coupling of rings to each other, and to the input and output bus waveguides. In this section we highlight several aspects of the ongoing research in microring resonator technology. We start with a review of the material systems used in the fabrication of microrings.

7.1 Material Systems

The fundamental requirement of a material system is that it have an index contrast sufficiently large to allow the fabrication of rings smaller than about 100 μm. This minimum index contrast is approximately 8%. Silicon waveguides with index contrasts in excess of 200% have been studied by Little et al. [32]. Chu et al. [33,34] have studied the compound glass Ta₂O₅:SiO₂ having an index contrast of about 20%. Silicon Oxynitride (SiON) has been studied for conventional as well as microring resonator technology [35]. The index contrast of SiON can be adjusted over the range of 0% to about 30%. Silicon Nitride with an index contrast of 30% has been studied by Bloom et al. [36,37] and Klunder et al. [38]. Compound glass is sputter-deposited, while the silicon-based materials can be deposited by chemical vapor deposition (CVD) or low-pressure chemical vapor deposition (LPCVD). Reactive Ion Etching (RIE) is the preferred method for patterning these types of materials. The foregoing materials are attractive for
their long-term reliability and for their compatibility with conventional semiconductor processing.

Polymer materials have several attributes that make them attractive, including ease of fabrication and planarization, an enhanced thermo-optic coefficient, UV sensitivity, and the ability to be doped with a wide range of other materials. Chen et al. have studied benzocyclobutene (BCB) based rings [39]. Rabiei has studied electro-optic polymers [40]. Polymeric materials can be processed by dry etching such as RIE or by photo patterning. Photo-patternable polymers have the advantage of ultra-smooth sidewalls and thus low scattering loss. Nano-imprinting technology has also been studied as a means for mass producing rings [41].

Semiconductor-based rings are attractive for their active and electro-optic properties. Rafizadeh et al. [42,43], Hryniewicz et al. [6], and Tishinin et al. [44] have fabricated GaAs-based rings. Grover et al. [45] and Rabus et al. [46] have studied InP-based rings. III-V semiconductor lasers integrated with rings have also been fabricated [47,48]. Semiconductor rings have been patterned by RIE and chemically-assisted ion beam etching (CAIBE). Figure 18 shows examples of first-, second- and third-order GaAs racetrack resonators fabricated at the University of Maryland [6].

Although high index contrast is necessary for reducing the fundamental bending-induced losses in rings, typically a higher index contrast implies higher scattering losses. Best results are obtained for devices that use moderate index contrasts (10%-25%) and those that have the smoothest sidewalls. A model for roughness-induced scattering and junction losses in semiconductor ring resonators has been developed and compared with fabricated devices [49].

### 7.2 Coupling Geometries

Two physical geometries have been studied for the coupling of energy from bus waveguides into and out of rings. These are lateral coupling and vertical coupling. In lateral coupling the ring and bus waveguides are in the same planar
layer and are evanescently side-coupled. A thin gap remains between the ring and bus as depicted in Figure 18 and this gap determines the coupling strength. Typical gaps are on the order of 100 nm to 500 nm. These gaps are close to the resolution limit of conventional lithography and, in fact, often fall below the lithographic resolution limit. E-beam lithography has often been necessary to pattern such fine gaps. Designs that use materials with larger index contrasts necessitate narrower gaps.

Variability in the ring-to-bus coupling strength leads to variability in the line shape, which is unacceptable for telecom devices. Vertical coupling has been developed as a method for controlling the coupling strength to a higher degree than etching narrow gaps. In vertical coupling the rings and the bus waveguides are in two different layers. The separation between the bus and rings is realized by a deposition step, rather than an etch step. A further advantage of vertical coupling is that different devices with different bandwidths can be realized using the same mask set, by simply adjusting the vertical separation during fabrication. Figure 19 shows the concept of vertical coupling. In vertical coupling it is

![Figure 19](image1.png)

Figure 19. Vertical ring-bus coupling scheme: (a) schematic of a vertically-coupled filter, (b) cross-sectional schematic showing vertical ring-bus coupling, and (c) scanning electron micrograph (SEM) of a fabricated such arrangement (courtesy of Little Optics, Inc.).

Figure 20. (a) Cross-grid array of microring resonators for large-scale array interconnections [33]; (b) alternative optical filter design using a hybrid resonator-DFB structure [55].
essential that all layers are planar. Suzuki et al. [50] achieved planarization by using an electron cyclotron CVD approach (biased-CVD) to overclad the core layers. Chu et al. [51,52] have developed a lift-off technique for planarization. Absil et al. [53] have developed a wafer bonding technique based on polymer bonding, while Tishinin et al. have [44] developed a wafer bonding technique based on wafer fusion. Wafer bonding allows for pristinely planar layers.

A further benefit of vertical coupling is for large-scale array interconnections as depicted in the cross grid array of Figure 20(a) [33]. In this array, the waveguides are in one layer and the rings are in a second layer. The waveguides are arranged in a Manhattan grid pattern with rings situated at the intersections. Each layer can be optimized separately. The ring layer is optimized to have high index contrast in the plane, while the bus layer is optimized to have low propagation loss, lower index contrast, and better fiber-matching dimensions.

7.3 Devices

Resonators are attractive building blocks because they can be used for a wide variety of photonic functions. As outlined in this chapter, they are particularly well suited to wavelength filters. Little et al. have studied rings for use in wavelength add/drop filters [5,54]. In Sections 4.1 and 4.2, higher-order filters were studied for improving the response shape. Rings can also be periodically coupled as shown in Figure 20(b), yielding a hybrid resonator-distributed feedback structure [54-56]. Madsen has studied more general arrangements of rings using ring-coupled Mach-Zehnder interferometers in order to achieve elliptic function responses [57,58]. Notch filters using Mach-Zehnder coupled
rings have also been fabricated and tested [59]. Figure 21(a) shows a GaAs ring coupled to an ultra-compact Mach-Zehnder for use as a notch filter. Figure 21(b) shows a simulation of the optical field distribution at wavelengths that are ON and OFF resonance. At wavelengths that are ON resonance the ring introduces a π-phase shift in one branch of the Mach-Zehnder, thereby imbalancing it. Filters with a second-order response, yet using a single ring can be realized by putting a controlled perturbation in the ring [60]. This type of ring supports hybrid counter-propagating modes and can be used as a narrowband reflection filter.

Rings are also very attractive for all-pass filters which can be used for fixed or tunable dispersion compensation [61]. Light that couples into the ring recirculates for an amount of time that depends on the wavelength and on the ring-bus coupling strength. The closer the wavelength is to a resonance, the longer the light dwells in the ring. There is a fundamental relationship between the amount of dispersion achievable in a specific ring, and the optical bandwidth [62]. Rings are attractive for dispersion compensation because they can be cascaded in series on the same chip.

Nonlinear interactions are enhanced in resonators because the amplitude inside the cavity is larger than the amplitude that is launched from the outside of the cavity. Rings have been used to enhance the efficiency of four-wave mixing for example. It has been shown by Absil et al. that four-wave mixing is enhanced by the sixth power of the resonator Q [63,64]. Nonlinear switching has also recently been demonstrated [65].

High-Q rings can be switched ON or OFF by applying absorption to them [66,67]. The absorption quenches the resonance. Although a high amount of absorption in the ring switches the ring OFF, the optical signal does not itself experience high attenuation because for high-Q resonators the ring and the bus are only weakly coupled.

Other novel devices include polarization rotators [68]. Polarization rotation in rings occurs when the ring waveguides have sloped sidewalls. The modes supported by rings with sloped sidewalls have hybrid polarization (a significant mixing of TE and TM field components), in contrast to the bus waveguides, which support fundamental modes whose field distribution is predominantly TE-like or TM-like. An incident TE or TM mode from the bus waveguide will excite the hybrid mode in the ring. This hybrid mode in turn excites both the TE and TM modes in the bus waveguide when it couples back to the bus.

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<sup>e</sup> where terms TE and TM are used to denote the directions parallel and perpendicular to the chip surface, respectively.
Wavelength filters need to be positioned very accurately to the particular channels they are to process. Thermal tuning can be used to dynamically position the filter resonance. Permanent resonance changes can also be induced, for example, by UV trimming [69,70].

8. Commercial Applications of Ring Resonators

As manufacturing technology matures, microrings and other types of resonators are finding increased use in commercial applications where their performance matches or exceeds that of conventional approaches. Their compact size is highly desirable for large-scale photonic integration, and it is expected that this technology will continue to penetrate the optical layer in systems. In this section, we give examples of commercially available products based on microrings.

8.1 Universal Demultiplexers

Microring resonator filters are particularly effective in network systems that are based on a banded architecture. In a banded architecture the frequency spectrum is subdivided into coarse sub-bands. Each sub-band further comprises a number of more narrowly separated channels. Sub-band architectures provide for
modular growth of system traffic. Figure 22(a) shows schematically the terminal end of network based on a banded architecture. In this particular architecture each sub-band is 200 GHz wide. The sub-bands carry four channels that are spaced by 50 GHz. At the terminal end a coarse (and inexpensive) band-splitting filter splits the sub-bands into independent ports supporting 200 GHz of bandwidth. A narrowband demultiplexer further separates the closely spaced channels on each sub-band. As network traffic grows, more sub-bands can be populated, or the number of channels within each sub-band can be increased, for example, by going to eight 25 GHz-spaced channels within the 200 GHz sub-bands.

Each narrowband demultiplexer within each sub-band serves the same purpose; it spatially demultiplexes the narrowly spaced channels. The difference between the demultiplexers in each sub-band is one of absolute frequency of the demultiplexed signals. An ideal demultiplexer is one which can demultiplex the four consecutive channels in any sub-band. Ring resonators are ideal for such an application. Rings have a periodic response with a periodicity that can be designed by choice of the appropriate ring radius. For example, a ring can be designed to have a periodicity of exactly 200 GHz. A demultiplexer comprised of four ring-based filters each with an FSR of 200 GHz could be used in any sub-band without having to be specialized for any one sub-band. Such a device is called a “colorless demux” or “universal demux”. Further, each ring filter can be tuned independently of any other filter, and this provides wavelength trimming or tracking on a wavelength-by-wavelength basis. This is particularly important for closely spaced channels. One may compare this with an AWG for example, where all channels must be tuned simultaneously.

An example of a commercial Universal Demux is shown in Figure 22(b-c) [22]. This device is manufactured by Little Optics, Inc., and can accommodate up to 32 channels at 25 GHz (800 GHz FSR). Each filter consists of a fifth-order microring cavity with the spectral response shown. The size of the optical chip is less than 1 cm by 5 mm.

8.2 Widely Tunable Wavelength Filters

Two-port tunable filters are ubiquitous in optical communication systems. They are widely used in broadcast-and-select architectures where they serve essentially as tunable receivers. They also find applicability in optical power monitors and performance monitors. Typical criteria call for wide tunability (at least 32 nm of tuning range), narrowband performance, tight frequency control, repeatability
Microring resonator filters based on a Vernier architecture provide desirable characteristics for tunable filter applications. Thermally tuned ring filters are solid state, yielding exceptional environmental stability. They are small and therefore consume significantly less thermal power compared with conventional planar optics. The Vernier configuration uses double filtering which improves the out-of-band rejection ratio significantly, and also allows for tuning that spans a range much larger than the natural FSR of each ring filter in isolation.

Figure 23. A simple, “Vernier-cascade” arrangement extends the effective free spectral range (FSR) of the drop-response of a filter: (a) schematic, (b) FSRs of the two individual rings show one matching resonance and two resonances which are suppressed in the total drop-port response. Small tuning of the resonance frequency of one ring permits a large tuning (in discrete steps) of the total filter as the next resonance in the comb is selected.

Figure 24. Drop-port spectral responses of Vernier-tunable filters: (a) cascade of two second-order filters fabricated by Lambda Crossing; (b) single and Vernier cascade of 5th-order filters fabricated by Little Optics, Inc. (courtesy of Lambda Crossing and Little Optics, Inc., respectively).

and long time reliability, low power consumption, and large out of band signal rejection.
The Vernier concept is illustrated in Figure 23 for single ring resonators. An input signal is filtered by a first ring having an FSR of FSR1. The output of the first ring, which consists of a comb of transmission peaks, is subsequently filtered by a second ring having an FSR of FSR2. There will only be appreciable signal at the final output when a particular wavelength is simultaneously resonant in both rings. All other non-coincident resonant wavelength peaks are suppressed, giving rise to a net drop port-response spectrum that has only one peak over a very large wavelength range. Figure 23(b) shows theoretical, stand-alone spectra from two rings having slightly different FSRs, with one particular wavelength being resonant in both rings simultaneously.

A tunable filter manufactured by Lambda Crossing is shown in Figure 24(a). This filter is based on a Vernier architecture that is composed of cascaded second-order filters. A tunable filter manufactured by Little Optics, Inc. is shown in Figure 24(b). This filter is based on a Vernier architecture that is comprised of cascaded fifth-order filters. Such Vernier-type filters give out-of-band rejection in excess of 60 dB. Further, the cascading of higher-order filters gives responses that have very rapid frequency roll-off.

9. Conclusion

Integrated Optics has a long history. The name originated at Bell Laboratories in the early 1970’s when many of the concepts presented here were first envisioned. In the intervening three decades numerous new ideas have emerged, notably the Arrayed-Waveguide Grating (AWG) multiplexer and demultiplexer [71]. However, wide acceptance of integrated optics in commercially deployed systems is still lacking. This may change with the advent of ultra-high bit-rate fiber optic transmission. The radiation Q’s of integrated optical components become adequate, and the tolerances of the components become less strict as the bandwidth of the channels increases. Linear signal processing devices for use in high bit-rate systems, like the ones described in this chapter, seem at the verge of wide-scale deployment. Already, micro-cavities are finding their way into commercial applications due not only to their size, but to their superior performance characteristics. This trend is expected to continue for the foreseeable future as fabrication technology improves.
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References
