GaAs Microcavity Channel-Dropping Filter Based on a Race-Track Resonator

M. K. Chin, C. Youtsey, W. Zhao, T. Pierson, Z. Ren, S. L. Wu, L. Wang, Y. G. Zhao, and S. T. Ho

Abstract— **We have demonstrated add–drop filters using racetrack-shaped resonators coupled to straight waveguides across gaps which are larger compared with the conventional microcavity ring resonators. The finesse and the maximum transmission are characterized and are shown to be determined uniquely by the round-trip loss and the coupling factor of the resonator.**

Index Terms—**Filter, microresonator, waveguides, nanophotonics, WDM.**

I. Introduction

MICRO-RING resonators [1], [2] may be used as the basis for a new class of wavelength-division-multiplexing (WDM) devices that offers potential advantages in performance, size and cost. Waveguide-coupled microcavity ring and disk resonators in AlGaAs–GaAs material system with high finesse (>100) and 22-nm free-spectral range (FSR) have been demonstrated [1]. The large FSR of these resonators results from their extremely small size (~ 10 μm diameter), made possible by the use of waveguides with a large lateral index contrast of 3.4 to 1. Such dimensions would conceivably enable realization of large-scale photonic integrated circuits with very high packing density, such as an optical cross-connect switching fabric demanded by future dense WDM systems.

The conventional GaAs–AlGaAs microring resonators are coupled to input and output waveguides via a "point contact," and therefore a very small gap, of the order of 100 nm, is required for sufficient coupling. A simple alternative is to insert a straight section in the coupling region, the length (l) of which can be adjusted alone to attain a given coupling factor while keeping the gap size (g) fixed. We call this a "racetrack" resonator [3]. This structure has been used in large-diameter ring lasers [4], [5], and has been proposed and analyzed for microcavity ring resonators [6]–[7], but we believe the present letter is the first demonstration of microcavity racetrack resonators. Typically, we have fixed g to be 200 nm, for which the fabrication is much more repeatable and tolerant. The coupling factor, being determined by l, can have a broader range of values, and can be designed to be the same even for resonators with different cavity lengths.

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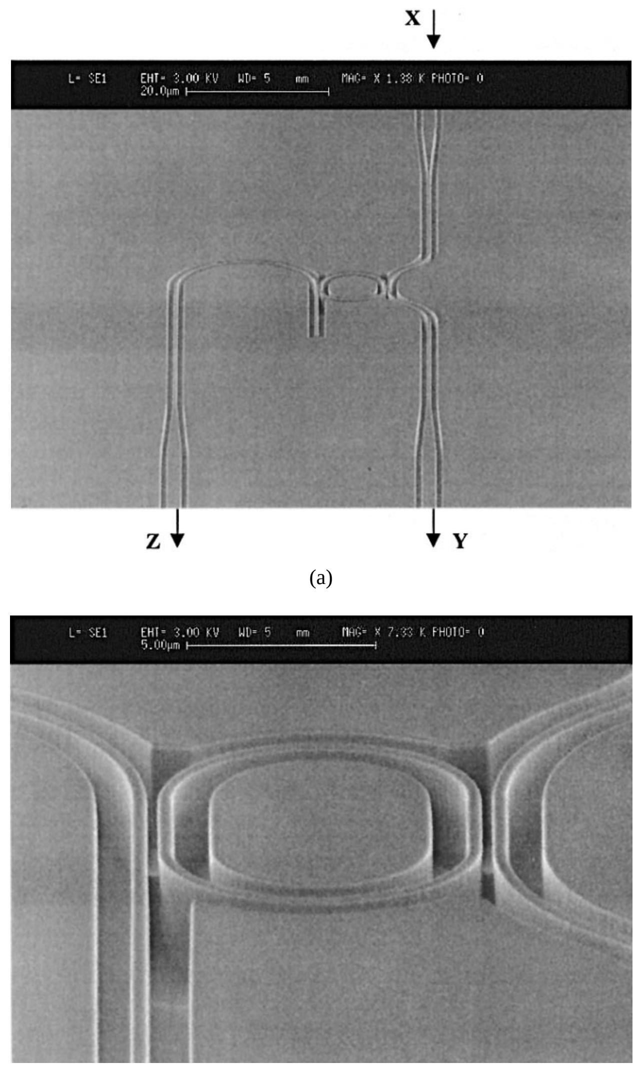

(a)

(b)

Fig. 1. Scanning-electron microscope images of (a) a resonator-based channel dropping filter and (b) the racetrack resonator.

II. Results

Fig. 1 shows scanning-electron microscope images of a resonator-based channel dropping filter and the race-track resonator. The devices are fabricated by electron-beam lithography and deep etching using inductively coupled plasma reactive ion etching (ICP-RIE). Surrounded by 2.5-μm-deep and 1-μm-wide trenches, the waveguides are 0.4 μm wide in the resonator and near the coupling region, but taper to 2 μm away from the resonator for easier input coupling and

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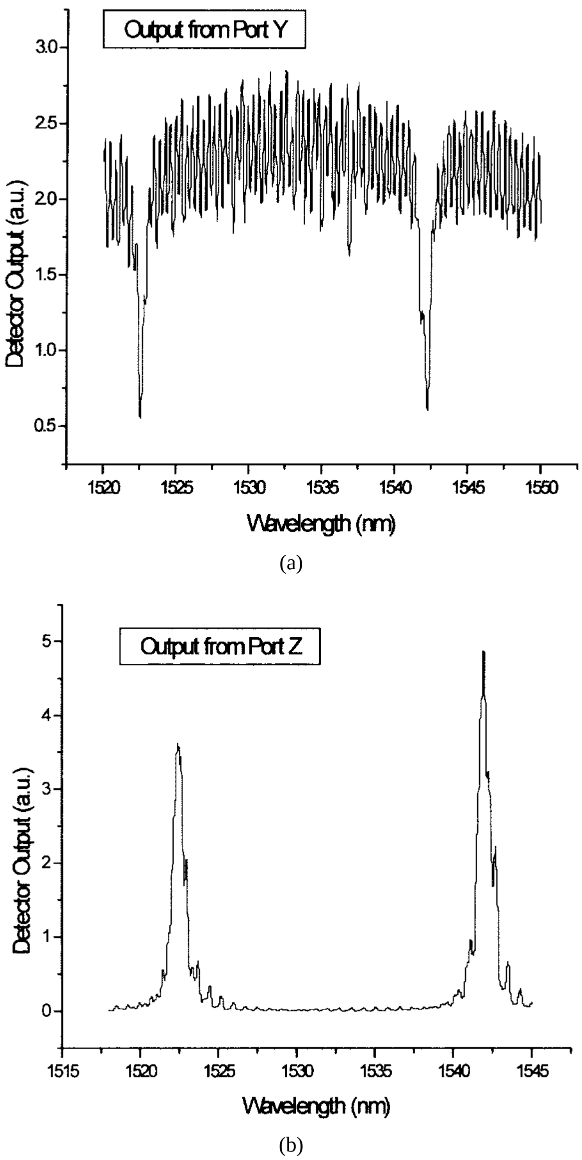

Fig. 2. The reflection and transmission spectra of a waveguide-coupled resonator with a cavity length of 31 μm, $g = 0.2$ μm and $l = 6$ μm, for the TM polarization.

reduced optical loss. The gap size is designed and measured to be the same for the two coupling regions. The waveguide structure is grown on GaAs substrate and consists of 2-μm-thick $Al_{0.6}Ga_{0.4}As$ lower cladding layer, 0.45-μm GaAs core layer, and 0.5 μm $Al_{0.6}Ga_{0.4}As$ upper cladding layer.

Resonator devices with various g and l are characterized with a tunable laser diode with center wavelength at 1550 nm. The laser light is lens-coupled into the input waveguide at port X [see Fig. 1(a)]. When the wavelength is off resonance with the resonator, the light is "reflected" and exits through port Y. When the wavelength is on resonance, the light is transmitted through the resonator and exits through port Z. Both the resonance wavelength and the coupling factor depend on polarization. For the case of a waveguide-coupled resonator with a cavity length of 31 μm, $g = 0.2$ μm and $l = 6$ μm, the reflection and transmission spectra for the TM polarization are shown in Fig. 2. The spectra also show the Fabry–Perot oscillations due to the uncoated waveguide facets. For the TE polarization, it turns out that the coupling is much weaker, and the resonance behavior is much less pronounced. The spectra show that the FSR is 20 nm, the full-width at half-maximum (FWHM) linewidth is 1 nm, and hence the resonator has a finesse of 20. Furthermore, the maximum transmission is about 80%. Another resonator, with $g = 0.2$ μm and $l = 4$ μm, has a FWHM linewidth as small as 0.2 nm (corresponding to a finesse of 100), but the maximum transmission is also much smaller.

III. Analysis and Design Considerations

The waveguide-coupled racetrack resonator is essentially a Fabry–Perot interferometer with the two couplers forming the mirrors. Since the couplers are designed and measured to be identical, with the same g and l, the mirrors can be taken to have the same reflectivity, $r_1 = r_2 = R^{1/2}$. The usual Fabry–Perot equations for the optical tansmission and reflection are then given by [8]:

$$\frac{I_T}{I_O} = \frac{t_{\max}}{1 + F\sin^2(\delta/2)}, \qquad \frac{I_R}{I_o} = \frac{r_{\min} + F\sin^2(\delta/2)}{1 + F\sin^2(\delta/2)} \tag{1}$$

and the finesse is given by

$$\mathcal{F} = \frac{2\pi}{2\delta_{1/2}} = \frac{\pi}{2\sin^{-1}\sqrt{1/F}} \tag{2}$$

where

$$t_{\max} = \frac{(1-R)^2 A}{(1-RA)^2}, \quad r_{\min} = \frac{(1-A)^2 R}{(1-RA)^2},$$
$$F = \frac{4RA}{(1-RA)^2}, \quad A = \exp(-\alpha L), \quad \delta = \frac{2\pi}{\lambda} n(2L)$$

I_o is the input intensity, L is half the cavity round-trip length, $t_{\max}$ is the maximum transmission, and $r_{\min}$ the minimum reflection. Note that in the lossless case $(A = 1)$ $t_{\max} = 1$ and $r_{\min} = 0$. Even though the reflectivities are equal, the presence of loss makes the mirrors unbalanced and reduces the transmittance. Our objective is to relate the measurable performance characteristics, finesse $(\mathcal{F})$ and maximum transmission $(t_{\max})$, to the device characteristics, round-trip loss $(L_{RT} = 1 - A^2)$ and coupling factor (P_c), which cannot be measured directly. The coupling factor is related to the mirror reflectivity by $R = 1 - P_c$. For the case of race-track resonator, if we neglect the loss within the coupling section, the coupling factor is given by

$$P_c = \sin^2\left(\frac{\pi}{2}\frac{l}{l_c}\right), \quad l_c = \frac{\lambda}{2(n_e - n_o)} \tag{3}$$

where l_c is called the coupling length, being the distance required to couple 100% of the power from one waveguide to the other. Such power transfer is due to beating or interference

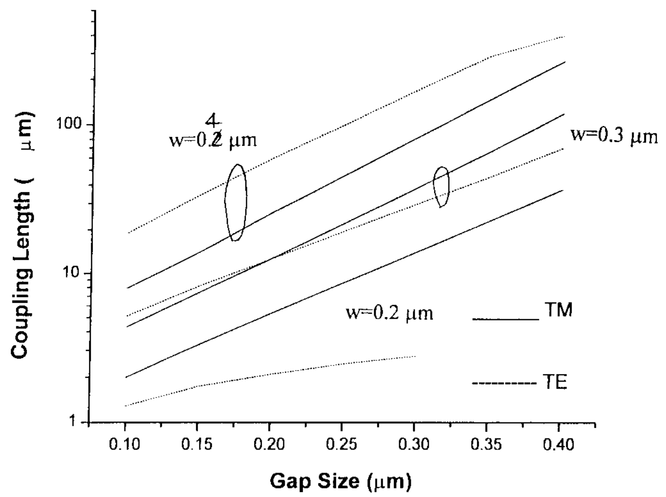

Fig. 3. Coupling length as a function of the gap size and the waveguide width (w), for both TE and TM polarizations.

between the two eigenmodes of the coupled-waveguide structure (called super modes), of which one is symmetric, with an effective index of n_e, and the other antisymmetric, with an effective index of n_o [9]. Fig. 3 shows the coupling length as a function of the gap size and the waveguide width (w), for both TE and TM polarizations, calculated using a full-vectorial finite difference mode solver.[1] The results reveal two significant features: (1) The coupling length can be extremely small, as small as a few microns in the case of $w = 0.2$ μm. (2) The coupling is polarization dependent. In particular, the coupling length is much shorter for TM than for TE when $w = 0.4$ μm, which explains the polarization dependence of the resonator behavior. For $g = 0.2$ μm, $l_c = 25$ μm for TM.

The achievable finesse and $t_{\max}$ are constrained by the coupling factor and round-trip loss in accordance with (1)–(2). These equations can be solved for P_c and L_{rt} in terms of $\mathcal{F}$ and $t_{\max}$, and plotted, as in Fig. 4, to give the combinations of P_c and L_{rt} required to achieve a given finesse or $t_{\max}$. Such a figure can serve as a useful guide to the design of racetrack resonators [10]. By the same token, P_c and L_{rt} can be determined uniquely from this figure if the finesse and $t_{\max}$ are known. For example, to achieve both high finesse (>100) and high $t_{\max}$ (>0.8), both P_c and L_{rt} have to be very small. For our experimental case of Fig. 2, where $\mathcal{F} = 20$ and $t_{\max} = 0.8$, the corresponding P_c and L_{rt}, as indicated by the solid dot in Fig. 4, are given by $L_{rt} = 0.03$ and $P_c = 0.13$. The value of L_{rt} implies a loss coefficient of $\alpha = 5$ cm^{-1}, which is consistent with the range of values obtained from straight-waveguide measurements. However, it should be noted that additional loss can arise in the resonator from the transitions between the straight waveguides and the curved waveguides. The value of P_c is also in agreement with that calculated directly from (3) using $l_c \sim 25$ μm and $l = 6$ μm.

In conclusion, we have realized the first channel-dropping filters using a race-track microresonator. We have characterized the device performance in terms of finesse and maximum transmission, and shown that they are related uniquely to the round-trip loss and the coupling factor, two fundamental characteristics of the resonator. Propagation loss in the cavity leads to an imbalanced Fabry–Perot even though the coupling factors (or mirror reflectivities) are identical. To achieve unity transmittance, one would in fact have to make the coupling factors slightly different to compensate for the loss.

[1] Optical Waveguide Mode Solver (OWMS), Apollo Photonics, Waterloo, Canada.

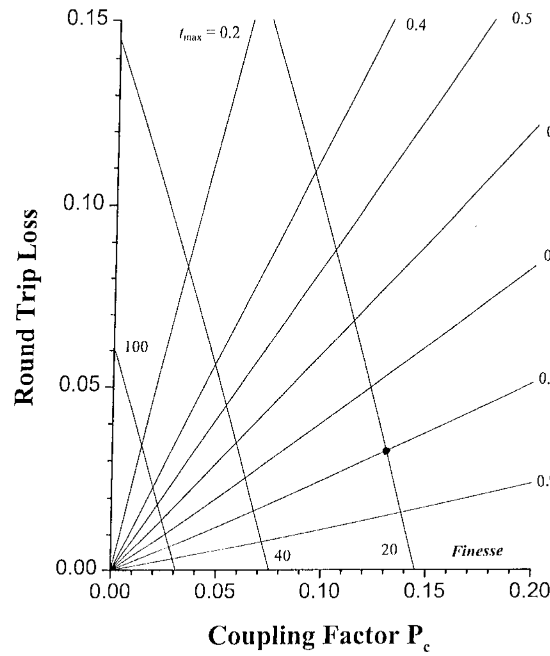

Fig. 4. Contour plots of constant finesse and constant $t_{\max}$, as a function of the coupling factor P_c, and the round-trip loss L_{rt}. The solid dot represents the experimental data discussed in text.

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