Prediction and suppression of strong dispersive coupling in microracetrack channel drop filters

Qin Chen,* Yue-De Yang, and Yong-Zhen Huang

State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, P.O. Box 912, Beijing 100083, China
*Corresponding author: chenqin@red.semi.ac.cn

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For a four-port microracetrack channel drop filter, unexpected transmission characteristics due to strong dispersive coupling are demonstrated by the light tunneling between the input–output waveguides and the resonator, where a large dropping transmission at off-resonance wavelengths is observed by finite-difference time-domain simulation. It causes a severe decline of the extinction ratio and finesse. An appropriate decrease of the coupling strength is found to suppress the dispersive coupling and greatly increase the extinction ratio and finesse, a decreased coupling strength can be realized by the application of an asymmetrical coupling waveguide structure. In addition, the profile of the coupling dispersion in the transmission spectra can be predicted based on a coupled mode theory analysis of an equivalent system consisting of two coupling straight waveguides. The effects of structure parameters on the transmission spectra obtained by this method agree well with the numerical results. It is useful to avoid the strong dispersive coupling region in the filter design. © 2007 Optical Society of America


Channel drop filters are widely used in wavelength division multiplexed systems to access one wavelength channel and leave the other channels unaffected [1]. Compact size, high finesse, and wide free-spectral region (FSR) characteristics have been demonstrated for optical filters consisting of single- and multiple-ring resonators laterally or vertically coupled with the add and drop waveguides [2–5]. In addition, filters based on a racetrack resonator were proposed to enhance the coupling efficiency [6,7]. In a recent work [8], we revealed that distributed mode coupling exhibits an unexpected behavior in finite-difference time-domain (FDTD) simulation of a microracetrack channel drop filter. The extinction ratio, defined as the ratio of the dropping power on resonance to the nearby off-resonance power, and finesse, defined as the ratio of the FSR to the linewidth of the on-resonance peak, are greatly reduced because the off-resonance signal also drops down to the drop port as an on-resonance signal in the strong dispersive coupling region. The effect is fatal to the practical application of the channel drop filter. It is necessary to investigate the transmission characteristics in detail with the dispersive coupling and find a way to suppress or avoid this effect.

In this Letter, strong dispersive coupling in a microracetrack filter is demonstrated directly by the light tunnelling of on-resonance and off-resonance signals between input–output waveguides and the resonator. An asymmetrical waveguide structure is found to largely suppress the dispersive coupling and increase the extinction ratio and finesse. Based on the coupled mode theory (CMT) analysis of an equivalent system consisting of two coupling straight waveguides, the profile of the coupling dispersion in a racetrack filter can be accurately predicted. First we simulate a racetrack channel drop filter by a two-dimensional (2D) FDTD technique as in Ref. [8] for the transverse magnetic (TM, $H_z=0$) mode. The structure is shown in Fig. 1, with the refractive indices of both the resonator and the input–output waveguides $n=3.2$, the width of the resonator $W_r=0.20 \mu m$, the radius $R=2.0 \mu m$ of the ring part, and the length $L=3.5 \mu m$ of the straight waveguide part in the racetrack, and the air gap $g=0.20 \mu m$. For the width of the input–output waveguides $W_g=0.20 \mu m$, the transmission spectra at the through port are plotted as the dashed lines in Fig. 2(a), where a large dip of the transmission around 1.55 $\mu m$ is observed. The minimum transmission at the off-resonance wavelength to the through port is only 9.3% at 1.5528 $\mu m$, labeled “a”; that is, more than 90% of the power drops down to the drop port at the off-resonance wavelength. The light tunneling process at a single wavelength is simulated with a single-frequency continuous exciting source by the 2D FDTD technique. The field distributions at the time of $2 \times 10^4$ time steps are plotted in Figs. 3(a) and 3(b) for the exciting sources at 1.5528 and 1.5688 $\mu m$ labeled “a” and “b”.

![Fig. 1. Schematic of a racetrack channel drop filter with the corresponding parameters labeled.](image-url)
mission spectra almost disappears, and the minimum transmission at the off-resonance wavelength of 1.6025 \( \mu m \), labeled “d,” is more than 96%. The stable field distributions at the on-resonance wavelength of 1.5825 \( \mu m \), labeled “c,” and off-resonance wavelength of 1.6025 \( \mu m \) are also demonstrated in Figs. 3(c) and 3(d). Most power at the on-resonance wavelength drops to the drop port, and very little power at the off-resonance wavelength drops to the drop port, as is required for a practical filter. The performance of the device shows an obvious improvement, where the extinction ratio around 1.55 \( \mu m \) increases 14.3 dB and the finesse increases by 8 times.

Although the asymmetrical waveguide structure can increase the extinction ratio and finesse, there is a disadvantage that the mismatch between the modes in input–output waveguides and the racetrack will reduce the coupling efficiency. In a practical case, the reduced coupling efficiency causes more cycles of light in the resonator, which suffers more loss due to the roughness at the sidewalls. If the location and the profile of the transmission dip can be predicted, we can exclude the strong dispersive coupling region from the working region of the devices.

Here, we propose a successful prediction of the strong dispersive coupling region of the racetrack filter based on the CMT analysis of an equivalent coupling system consisting of two single-mode straight waveguides separated by an air gap. \( A_0(x) \) and \( B_0(x) \) are assumed to be the fundamental mode distribution of the two isolate waveguides. Within the weak coupling region, two coupled modes \( C_1(x,z) \) and \( C_2(x,z) \) are [9]

\[
C_1(x,z) = [\alpha_2 A_0(x) + B_0(x)]e^{j\beta_1 z},
\]

\[
C_2(x,z) = [\alpha_2 A_0(x) - \gamma B_0(x)]e^{j\beta_2 z},
\]

where \( \beta_1 \) and \( \beta_2 \) are the propagation constants and \( \alpha_1, \alpha_2, \) and \( \gamma \) are coefficients. When the widths of the two waveguides are equal, i.e., when there is a sym-
metrical coupling system, then $\beta_1=\beta_2$ and $\alpha_1=\alpha_2=\gamma=1$. The field distributions in the two coupled waveguides should be

$$A(x,z) = \alpha_1 A_0(x) e^{i\beta_1 z} + \alpha_2 A_0(x) e^{i\beta_2 z},$$

$$B(x,z) = B_0(x) e^{i\beta_1 z} - \gamma B_0(x) e^{i\beta_2 z}. \tag{4}$$

The initial condition is set to be $A(x,0)=1$ and $B(x,0)=0$ (i.e., $\gamma=1$). We define the transmission as

$$T = \frac{|A(x,L')|^2}{|A(x,0)|^2} = \frac{|\alpha_1 e^{i\beta_1 L'} + \alpha_2 e^{i\beta_2 L'}|^2}{|\alpha_1 + \alpha_2|^2}, \tag{5}$$

where $L'$ is the effective coupling length. By resolving the wave equation in the five-layer slab waveguide system, we can obtain $C_1$, $C_2$, $\beta_1$, and $\beta_2$ and then obtain transmission spectra from Eqs. (1), (2), and (5).

In Fig. 4, we show the one-cycle transmission spectra by FDTD simulation as the solid curves and the analytical results of $T$ by CMT as scatters. In Fig. 4(a), the transmission dip in the spectra at the through port shifts to shorter wavelengths with an increase in $L$. The center of the dip is located around 1.55 $\mu$m at $L=3.5 \mu$m. We can see that the results of CMT agree well with the numerical results. For each pair of line and scatterings, coupling length $L'$ used in CMT is 1.3 $\mu$m longer than $L$ used in FDTD simulation because the curved part of the racetrack has extra coupling with the straight waveguide, which increases the effective coupling length. From Fig. 4(b), we can see that the center wavelength of the transmission dip shifts to longer wavelength with an increase in $g$. The analogous relation can be observed in Fig. 4(c) with the increase of waveguide width at $W_g=W_0$. So we conclude that the transmission dip appears in a shorter-wavelength region in the case of stronger coupling, i.e., a longer straight part of the racetrack, narrow gap, and narrow waveguides. The results of an asymmetrical coupling structure are shown in Fig. 4(d). For a better fit between the results from FDTD and CMT, the widths of the waveguides used in CMT and FDTD have very small differences, less than the space steps in the FDTD. The coupling dispersion is greatly suppressed with the increase in the asymmetry, where the spectra is almost a flat line at $W_g=0.24 \mu$m with a very weak coupling dispersion. The extinction ratio and finesse are expected to be held at the high values shown in Fig. 2(b).

In conclusion, we have presented unexpected strong dispersive coupling in racetrack filters. An asymmetrical waveguide structure is proposed to suppress the phenomenon and shows an obvious improvement of the extinction ratio and finesse. Based on CMT analysis of two coupling straight waveguides, the profile of the coupling dispersion in the transmission spectra of the filter can be reasonably predicted, which is useful for excluding the strong dispersive coupling region from the working region of the devices. In addition, the redshift of the dip in the transmission spectra is observed for racetrack filters with a short straight waveguide part, large air gap, and wide waveguide.

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References


