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Optimization of Resonant Channel-Dropping Filter in WDM System

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ABSTRACT

The several parameters are optimized to improve the performance of channel-dropping filter(CDF) using quater-wave shifted DFB resonators combined with waveguide couplers. The ratio of the grating strength to the coupling coefficient and the mirror grating length of the CDF are optimized to achieve the improved transfer characteristics and to support high Q to be utilized in WDM system.

Ⅰ. Introduction

The wavelength division multiplexing(WDM) is a promising approach to high bit rate optical communication and would be used to increase the bit rate by utilizing the very large bandwidth of optical fibers. The bit rates accessible to electronic switching are of the order 100 Gbps. If the communication is at a wavelength around 1.53 μm and each channel is to be filtered efficiently, one needs optical filters of the order 0.5Å bandwidth. The optical filters should transfer the radiation within the band to the receiver without perturbing the radiation outside the band.

Quarter-wave shifted distributed feedback resonators are useful as laser diode resonators because they provide a resonance at the center of the grating stop-band that is of higher Q than the resonances to either side of the stop band[1][2]. Alferness and Cross's filter is tunable but is not sufficiently narrow band to be used for the WDM system[3]. Kazarinov described and analyzed a narrow-band reflector that uses a DFB resonator[4]. His reflector has narrow band and cavity coupled to a waveguide by its fringing fields. When the cavity is off resonance, it does not affect the transmission in the waveguide, allowing full transmission having limit in fabrication. Haus and Lai invented a narrow-band reflector which uses quarter-wave shifted distributed feedback resonator that is excited by light at the Bragg wavelength from an evanescently side-coupled bus waveguide[5][6]. For a single side-coupled resonator, a maximum of 50% of the light can be shifted from the bus waveguide to the tap-off waveguide. They showed a channel dropping filter with the proper placement of a second side-coupled resonator, up to 100% of the on-resonant light that travels along the bus can be shifted to the tap-off waveguide[7]. Damask applied the channel-dropping filter to the WDM system and made practical design of side-coupled quarter-wave shifted distributed-Bragg resonant filter from Haus and Lai's theoretical analysis[8][9]. The narrow bandwidth and performance of channel dropping filter is dependent upon filter parameters.

In this paper, channel dropping filter has been optimized to support high Q and improve the transfer characteristics. The field profiles are derived from the coupled-mode equations and analogies to lumped resonators placed along transmission lines. A global design space, parametrized by the grating strength, κ, the grating length L_{1b}, and the wavelength coupling

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coefficient μ is used to show the range of filter resonance line width and the transmission coefficient can be obtained.

Ⅱ. Side Coupled Reflector

Four basic coupled equations are required to describe the side-coupled resonator operation. There are two waveguides, each of which guide forward and backward traveling waves. the wave envelopes are A_i and B_i for the forward and backward waves, respectively in Fig. 1. The index i refers to the waveguide. The basic envelope equations [5] are

$$\frac{dA_1}{dz} = -j\delta A_1 + \chi B_1 - j\mu A_2 \tag{1}$$

$$\frac{dB_1}{dz} = +j\delta B_1 + \chi A_1 + j\mu B_2 \tag{2}$$

$$\frac{dA_2}{dz} = -j\delta A_2 - j\mu A_1 \tag{3}$$

$$\frac{dB_2}{dz} = +j\delta B_2 + j\mu B_1 \tag{4}$$

where the detuning parameter is $\delta = (\omega - \omega_0)/v_g$. The sign of κ, the grating strength, is arbitrary, but it must be consistent across the discontinuity at $z=0$. That is, κ has reversed sign across the boundary. κ is positive for $z<0$. The coupling strength parameter is μ.

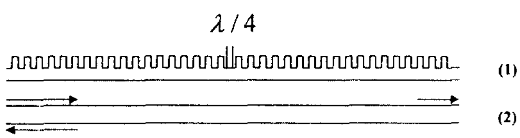


Fig. 1 Schematic of the resonant reflector.

Approximate solutions along waveguide 1 are constructed by ignoring the coupling to waveguide 2 and the power leakage at the end of the gratings. The source-free "ring-down" of the resonator is then considered. The out-going fields along waveguide 2 are calculated by including the waveguide coupling. Then the solutions are time reversed. The set of equations that result is an elegant way to correctly construct the effect of a symmetric excitation of the resonator. In this context, symmetric means to the simultaneous excitation of the resonator from both sides. The forward and time-reversed solutions are then added to generate a steady-state standing wave solution along the bus. This solution describes the steady-state interaction of the bus and the resonator. It will be found that only the symmetric field along waveguide 2, as referred to the symmetry of the resonator about the quarter-wave shift, couples to the antisymmetric field along waveguide 1. The antisymmetric field along waveguide 2 does not couple. It can be free to add the symmetric and antisymmetric solutions along waveguide 2 as necessary to demonstrate reflection.

The near-resonance spectrum can be calculated with the quality factor Q. The loss in the resonator is attributed to the energy that escapes the cavity by coupling to the lower waveguide. The power that escapes is

$$P_e = 2 \times 4\,|\mu/\chi|^2\, A_0^2 \tag{5}$$

The quantity $4\,|\mu/\chi|^2\, A_0^2$ is the power that escapes through one end. Taking into account the forward and backward waves on each side of the quarter-wave shift, the total energy in an isolated resonator with semi-infinite gratings is

$$W = 2 \times 2 \times \frac{A_0^{\,2}}{2\chi v_g} \tag{6}$$

The width of the resonance with respect to the grating stopband is

$$\Delta\omega = 2\,\Delta\omega_s\,|\mu/\chi|^2 \tag{7}$$

where $\Delta\omega_s = 2 v_g \chi$. Taking a reported value of grating $\chi = 200\ cm^{-1}$, and a coupling constant of $\mu = 5\ cm^{-1}$, the FWHM of the resonance fills 0.125% of the stopband. This small filling factor makes receivers based on optical resonance very attractive.

Ⅲ. Single Side-Coupled Receiver

This section covers the single side-coupled (SSC) receiver, which can detect up to 50% of the on-resonant signal. Only small modification to the resonant reflector is required to convert it into a receiver. Consider the energy within the side-coupled resonator. That power is spectrally pure to within the resonance FWHM, which is dictated by Q. A fraction of the resonant energy can be tapped off by shortening one side of the resonator grating. The Q factor of the receiver is not broadened until the power that escapes from the side of the grating is on the same order as that which escapes by side coupling to the bus. The tapped-off energy is spatially separated from the bus and can be guided to a detector.

Like the side-coupled resonant reflector, the SSC receiver is constructed with two waveguides, one of which supports the grating resonator. Unlike the side-coupled reflector, one end of the grating is shortened to tap off power in the resonator. A waveguide on which the resonator grating is etched continues beyond the grating to guide the received power to its destination.

Fig. 2 is a schematic of the SSC receiver and its associated transmission line analogy. The lengths of the gratings on either side of the quarter-wave shift are L_a and L_b, with $L_a > L_b$. The energy that leaks out from the length L_b is "dissipated" by the load. This dissipation is included in the transmission line model by adding a resistor to the LC parallel combination. Clearly, to maximize the power dissipated in the load resistor, the load resistance must be

$$R = 2Z_0 \qquad (8)$$

With this value of R, 50% is the resonant power is dissipated by the load, while 25% of the resonant power is transmitted and 25% is reflected. The internal and external Q's of the system can be used to determine the length L_b that meets the condition of (8).

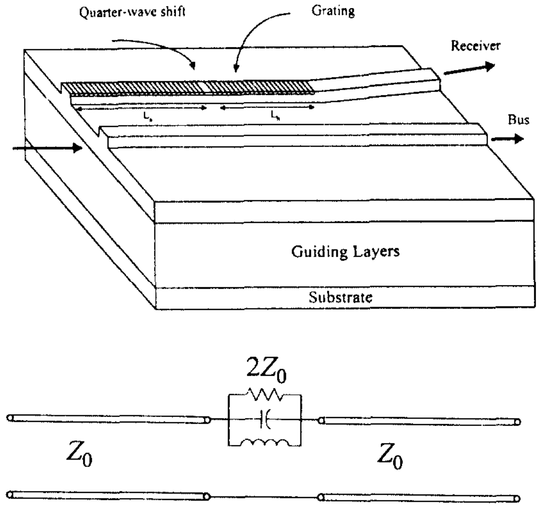


Fig. 2 Top: Schematic of the single side-coupled receiver. Bottom: Transmission line model of the receiver.

The power that escapes from the resonant system to the bus is determined by the external Q_e of the system. The energy dissipated by the load[7] is

$$\frac{1}{Q_d} = \frac{G}{\omega_0 C} = \frac{2v_g\chi}{w_0}\ e^{-2\chi L} \qquad (9)$$

Using (7) and (9) to satisfy condition (8) determines the length L_b:

$$L_b = \frac{1}{\chi}\ \ln\left(\frac{\chi}{\sqrt{2}\,\mu}\right) \qquad (10)$$

We have used equations that define the quality factor Q to arrive at the optimal length of the receiving arm L_b. Physically, there is a crossover in dominance between the two loss mechanisms of the resonant reflector. With very long gratings, the loss is dominated by the power that escapes to the bus. For short gratings, the loss is dominated by the power that escapes the ends of the resonator. The optimum value of L_b is determined when the two loss mechanisms balance one another.

The Q_{total} of the system is reduced by a factor of two when the receiving arm is taken as length L_b, as governed by (10). Therefore the receiver bandwidth is twice that of the resonant reflector. Nonetheless, state-of-the-art values of χ can allow upwards of one hundred channels to be placed within the stopband.

Ⅳ. Channel Dropping Filter

The narrow resonance width of the single side-coupled receiver, with respect to the grating stopband width, makes that receiver very attractive for wavelength-division multiplexing and demultiplexing. The drawback is that only 50% of the power is directed to a detector, while the difference remains on the bus. The channel-dropping filter (CDF) overcomes this limitation by adding a second side-coupled resonator.

Fig. 3 depicts a planar implementation of the CDF. A second side-coupled resonator is added on a third waveguide and is weakly coupled to the bus. Fig. 3 illustrates the CDF schematic and its corresponding transmission line circuit. All of the grating lengths other than L_{1b} are large. The second grating, called the "mirror" grating, is simply an additional resonant reflector that was considered in Section II. The phase plane of the mirror grating is shifted forward by one quarter wavelength with respect to the plane of the receiver grating. The transmission line circuit is used to demonstrate the behavior of this grating configuration.

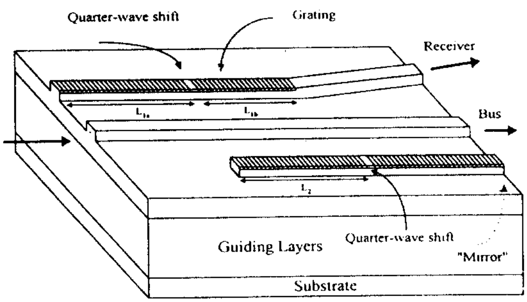


Fig. 3 Schematic of the resonant channel-dropping filter.

On resonance, both parallel LC combinations are open circuits. However, the mirror LC pair is quarter-wave shifted forward with respect to the receiver RLC combination. Therefore, the mirror appears to the receiver as a short, thereby terminating the transmission line. Now one can choose $G = Y_0$ to maximize the power dissipated by the load. In this case, 100% of the on-resonant power is transferred to the load while no power remains on the bus.

The length of truncated grating, L_{1b}, is given by equating $G = Y_0$.

$$L_{1b} = \frac{1}{\chi} \ln\left(\frac{\chi}{2\mu}\right) \tag{11}$$

The resonance width of the channel-dropping filter with respect to the stopband [7] is

$$\Delta\omega_{cdf} = 4\,\Delta\omega_s\,|\mu/\chi|^2. \tag{12}$$

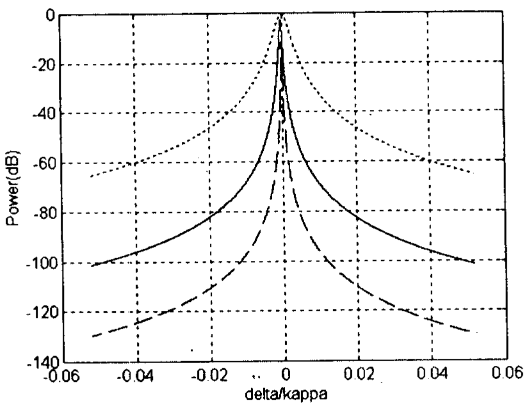
We arrive at (12) by noting that a second side-coupled resonator has been added and the load of the truncated resonator has been doubled.

One-hundred percent of the on-resonance power is transferred to the receiver waveguide, at the expense of the signal on the bus. Off-resonance signals are transmitted without distortion. Outside of the stopband there is little interaction of the bus with the resonators.

Ⅴ. Discussion

The channel-dropping filter design uses a grating strength of $\chi = 200\ cm^{-1}$, a coupling coefficient of $\mu = 10\ cm^{-1}$, $L_{1a} = 250\ \mu m$, $L_{1b} = 140\ \mu m$, $L_2 = 250\ \mu m$, optical index of $n = 3.5$, and zero loss. These numbers are all reasonable for group III-V compound structures when the loss is compensated by gain. The wavelength considered is $\lambda_0 = 1.53\ \mu m$.

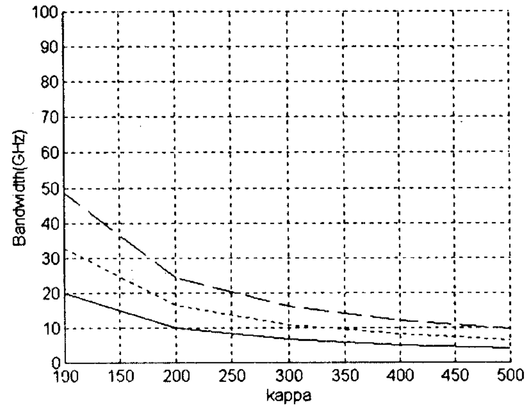
Fig. 4 shows that the signal spectrum of the channel dropping filter is dependent on the ratio of the grating strength κ to the coupling coefficient μ. As κ/μ increases, the narrow bandwidth is obtained. It is important to find optimum value of κ/μ with considering fabrication. The grating strength κ is evaluated from a field-theoretical approach. While many authors substitute simple waveguide field distributions to find an analytical solution, here a general computational expression for an arbitrary two-dimensional structure is used. The coupling coefficient μ is obtained by a field theoretical approach. That is local in that the overlap integral that defines μ requires point-for point information of two mode profiles. The coupling coefficient μ is a measure of the strength of overlap between the two spatially separated, weighted by the index difference between the core and cladding. A waveguide does not effect the mode pattern of its neighbor in the weak coupling region. When the waveguide separation decrease, the strong-coupling region. The admixture between the coupled systems is a measure of the loss of distinction between the modes. This mode admixture degrades the response of the filter [10]-[12].



: $x/\mu=10$, ——: $x/\mu=25$, ----: $x/\mu=50$

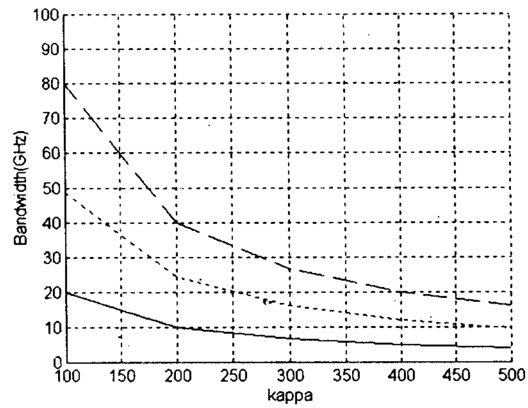
Fig. 4 Signal Spectrum of the Channel Dropping Filter (CDF)

The bandwidth of CDF also varies with receiver length L_{1b} with fixing (10 cm^{-1}) in Fig. 5 to Fig. 8. The range is between 50 GHz and 4 GHz in which κ varies from 100 cm^{-1} to 500 cm^{-1} in Fig. 5 through Fig. 7. It is shown that the narrow bandwidth needs the large length L_{ib} but we should consider the device size. Also Fig. 6 show that the desirable bandwidth is obtained at the large length L_2. Fig. 7 and Fig. 8 show the output transmittances on bus versus L_{1b} and L_2, respectively.



L_2 (——:139 μm, ⋯:127 μm, ----:117 μm)

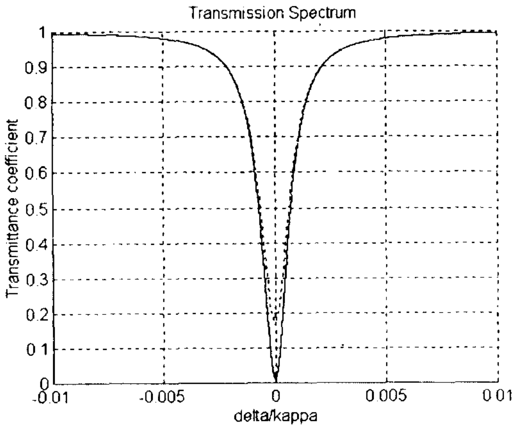
Fig. 5 Bandwidth of CDF depending Mirror Grating Length L_2 (μ: 10 cm^{-1}, κ: 100 cm^{-1}~500 cm^{-1})



L_{1b} (——:149 μm, ⋯:127 μm, ----:115 μm)

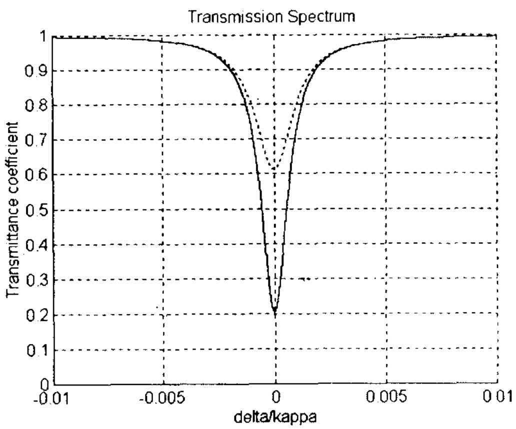
Fig. 6 Bandwidth of CDF depending Receiver Grating Length L_{1b} (μ: 10 cm^{-1}, κ: 100 cm^{-1}~500 cm^{-1})

The stopband is of the order of 4000 GHz and the optimum filter bandwidth is about 9 GHz. To avoid the spurious response outside the stopband, only the central half portion of the stopband can be used. The bandwidth can be accommodate 45 channels spaced 5 times the channel width apart. These results show that the design of such a filter bank is realistic.



L_2(—— : 250 μm, ---- : 190 μm)

Fig. 7 Relation of Transmittance Coefficient on the Bus to Mirror Grating Length L_2 (μ: 10 cm^{-1}, κ: 100 cm^{-1}~400 cm^{-1})



L_{1b}(—— : 180 μm, ---- : 145 μm)

Fig. 8 Relation of Transmittance Coefficient on the Bus to Receiver Grating Length L_{1b} (μ: 10 cm^{-1}, κ: 100 cm^{-1}~400 cm^{-1}).

Ⅵ. Conclusions

The several parameters are optimized to improve the performance of channel-dropping filter(CDF). The bandwidth of CDF has been made narrower than the stopband of the grating and improved in transfer characteries after optimizing. It is very important to optimize the grating strength κ, the coupling coefficient μ, receiver length L_{ib}, the length L_2 of the second side-coupled resonator to arrive at a narrow band channel-dropping filter.

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References

1. H. A. Haus and C. V. Shank, "Antisymmetric tape of distributed feedback lasers," *IEEE J. of Quantum Electron.*, vol. 12, no. 9, pp. 532-539, September 1976.
2. K. Utaka, S. Akiba, and Y. Matsushima, "λ/4-shifted InGaAsP/InP DFB lasers by simultaneous holographic exposure of positive and negative photoresists," *Electron. Lett.*, vol. 20, no. 24, pp. 1008-1010, November 1984.
3. R. C. Alferness and P. S. Cross, "Filter Characteristics of codirectionally Coupled Waveguide with Weighted Coupling," *IEEE J. of Quantum Electron.*, vol. 14, no. 11, pp. 843-847, November 1978.
4. R. P. Kazarinov, C. H. Henry, and A. Olsson, "Narrow-Band Resonant Optical Reflectors and Resonant Optical Transformers for Laser Stabilization and Wavelength Division Multiplexing," *IEEE J. of Quantum Electron.*, vol. 23, no. 9, pp. 1419-1425, September 1987.
5. H. A. Haus and Y. Lai, "Narrow-Band Distributed Feedback Reflector Design," *IEEE J. of Lightwave Technology*, vol. 9, no. 6, pp. 754-760, June 1991.
6. H. A. Haus and Y. Lai, "Theory of Cascaded Quarter Wave Shifted Distributed Feedback Resonators," *IEEE J. of Quantum Electronics*, vol. 28, no. 1, pp. 205-213, January 1992.
7. H. A. Haus and Y. Lai, "Narrow-Band Optical

Channel-Dropping Filter," *IEEE J. of Lightwave Technology*, vol. 10, no. 1, pp. 57- 62, January 1992.

8. J. N. Damask and Hermann A. Haus, "Wavelength-Division Multiplexing using Channel-Dropping Filters," *IEEE J. of Lightwave Technology*, vol. 11, no. 3, pp. 424-428, March 1993.
9. J. N. Damask, "Practical Design of Side-Coupled Quarter-Wave Shifted Distributed-Bragg Resonant Filters," *IEEE J. of Lightwave Technology*, vol. 14, no. 5, pp. 812-821, May 1996.
10. H. A. Haus, W. P. Huang, S. Kawakami, and N. A. Whitaker, "Coupled-mode theory of optical waveguide," *IEEE J. of Lightwave*, vol. 5, no. 1, pp. 16-23, January 1987.
11. M. R. Ramadas et. al. "Analysis of Absorbing and Leaky Planar Waveguides: A Novel Method," *Optics Letters*, vol. 14, no. 7, pp. 376-378, April 1989.
12. H. A. Haus and D. A. B. Miller, "Attenuation of Cutoff Modes and Leaky Modes of Dielectric Slab Structures," *IEEE J. of Quantum Electron.*, vol. 22, no. 2, pp. 310-318, February 1986.

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