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Novel Optical Wavelength Interleaver based on Symmetrically Parallel-Coupled and Apodized Ring Resonator Arrays

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ABSTRACT

Optical ring-resonators could be used to synthesize filters with low crosstalk and flat passbands. Their application to DWDM interleaving has been proposed and investigated previously. However, a number of important issues related to this topic have not yet been considered and appropriately addressed. In this paper, we propose a novel scheme of a symmetrically parallel-coupled ring resonator array with coupling apodization. We show that it can be used to construct a wavelength interleaver with good performance and compact size. Various design factors have been considered. An optimization procedure was developed based on minimizing the channel crosstalk in the through and drop ports simultaneously by adjusting the ring-bus coupling coefficients. We show that apodization in coupling could suppress channel crosstalk effectively by choosing the optimal coupling coefficients. We also introduced the equalization of both the input and output coupling coefficients to eliminate notches in the passband. For a 50 - 100 GHz DWDM applications, four rings is found to be the best choice for array size. A four-ring filter achieves crosstalk -24 dB, insertion loss at resonance <1 dB, and good passband flatness (shape factor >0.6).

Keywords: WDM passive filters, ring resonators, integrated optics, planar waveguides

1. INTRODUCTION

The increasing demand for bandwidth in optical telecommunications networks is presently satisfied by increasing channel density. However, for channel spacing less than 100 GHz, producing multiplexers with low crosstalk and insertion loss becomes very challenging. Using interleavers can alleviate this problem. Interleavers combine two separate streams of channels into one stream with half the channel spacing (Fig. 1). Likewise, deinterleavers split one stream into two. This flexibility in channel spacing permits higher channel densities while allowing for relatively inexpensive multiplexers with wide channel spacing to be used.

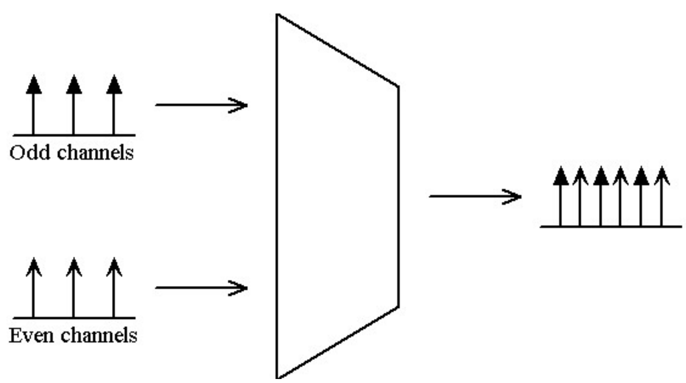

Figure 1. Interleaver function

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Interleavers are commonly produced using cascaded Mach-Zehnder interferometers (MZI's). This type of filter can be implemented using integrated optics. However, even the smallest designs occupy substantial wafer area, adding significantly to the cost of these devices and limiting their potential for integration with other devices on the same chip. Ring resonator filters, on the other hand, are much smaller, with ring diameters ranging from several microns to several millimeters. Like MZI's, they can be cascaded to synthesize higher order filters.

Ring resonators can be coupled in parallel via bus lines, as shown in Fig. 2. The separation between the rings is L_c, and the radius of each ring is R. The incoming wavelength division multiplexed (WDM) signal enters the filter at port P_{in}. Channels at resonant wavelengths exit at the drop port P_{drop}, while non-resonant wavelengths continue through to port P_{thru}. This configuration of rings is analogous to a DFB grating in that each ring functions as a reflection element.[1] In comparison with Bragg reflectors, however, ring resonators are wavelength selective and the reflection from each ring is much larger.

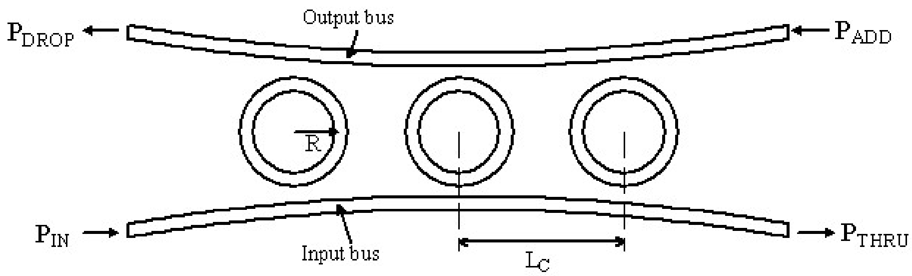

Figure 2. Ring resonators in a parallel-coupled configuration

For a single ring, resonance occurs when the ring circumference equals an integral multiple of the wavelength. The ring has a periodic spectrum with free spectral response equal to $FSR = c / (2n_r pR)$, where n_r is the ring effective index. The spectral response is a function of the coupling coefficients between the ring and the input and output buses, and dissipative loss in the ring itself. For coupled rings, the spectral response is also determined by the magnitude and phase difference between the reflected signals from each ring. Introducing more rings increases the number of poles (resonances) and zeros (transmission nulls). Tailoring of the passband shape is possible by adjusting the coupling coefficients.

Previous papers on parallel-coupled ring resonators have mainly dealt with their application to single-channel drop filters.[1-3] Griffel[4] mentioned their use as periodic filters for application such as interleaving. Unlike this paper, our filter design has equal apodisation of both input and output coupling coefficients and considers the spectra of both the drop and through output ports. As will be explained, this is important for interleaver design.

Melloni[5] considers two possible ways of designing a periodic parallel-coupled ring resonator filter. A periodic filter can be made with either L_c equal to an odd multiple of a quarter wavelength or L_c equal to a multiple of a half wavelength. In the former case, however, periodicity over the whole operating frequency band of the filter requires L_c to be as small as possible, necessitating highly elliptical rings. This is impractical, as bending loss will be very high at the narrow end of the ellipses, and coupling between the rings and buses will be difficult to control. The latter case does not suffer from this restriction, and circular rings are possible. Although the passband shape is not as good as the former case, it is still acceptable if a sufficient number of rings and apodization of the coupling coefficients is used, as will be demonstrated in this paper. Therefore, the former case is appropriate for single channel drop filters, whereas the latter case is preferable for periodic filters.

Ring resonators can also be coupled in series (Fig. 3), however the parallel configuration is less sensitive to fabrication variations since precise matching of the resonant frequencies of each ring is not vital. Further, the insertion loss of a series-coupled filter increases considerably when a small amount of dissipative loss is added to the rings. This is not the case for a parallel-coupled filter.

In this paper, interleaving filters consisting of parallel-coupled ring resonators will be designed. This type of filter has the advantages of small size and insensitivity to resonance wavelength and dissipative loss in the rings. Requirements on these filters include periodic response, box-like passbands, low insertion loss, low crosstalk, low chromatic dispersion, and fast response times. This paper considers only the magnitude response, and temporal response will be deferred to another paper. Emphasis will be placed on achieving performance comparable to commercial planar waveguide interleavers. Equalization of the input and output coupling coefficients will be shown to be important, as will exponential apodization of those coefficients. Optimization of both the drop and through ports will be done simultaneously, unlike previous treatments of periodic ring resonator filters. An optimized 50 - 100 GHz deinterleaver consisting of a four-ring array will be shown to have crosstalk of -24 dB, insertion loss at resonance <1 dB, and shape factor >0.6.

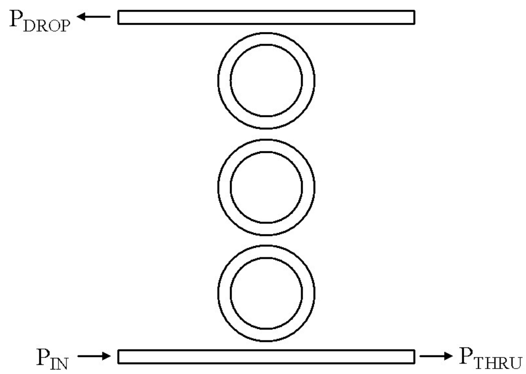

Figure 3: Ring resonators in a series-coupled configuration

2. FILTER SYNTHESIS THEORY

The transfer matrix method outlined by Grover et al.[2] was used to calculate the transmission spectra of the ring resonator arrays. The transfer matrix of a single ring is given by

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} c \\ d \end{bmatrix} \tag{1}$$

where

$$T_{11} = \frac{1-\tau_1\tau_2 a_r^2 e^{-j\Delta\omega_r t_r}}{\tau_1 - \tau_2 a_r^2 e^{-j\Delta\omega_r t_r}},$$

$$T_{12} = -T_{21} = \frac{\kappa_1\kappa_2 a_r e^{-j\Delta\omega_r t_r/2}}{\tau_1 - \tau_2 a_r^2 e^{-j\Delta\omega_r t_r}}, \text{ and} \tag{2}$$

$$T_{22} = \frac{\tau_1\tau_2 - a_r^2 e^{-j\Delta\omega_r t_r}}{\tau_1 - \tau_2 a_r^2 e^{-j\Delta\omega_r t_r}}.$$

Here, *a*, *b*, *c*, and *d* are the signals at the input, drop, through, and add ports respectively. κ_1 and κ_2 are the input and output coupling coefficients, and $\tau_1^2=1-\kappa_1^2$, $\tau_2^2=1-\kappa_2^2$. $a_r^2=\exp(-\alpha\pi R)$ is the amplitude attenuation for a complete circuit of the ring. α is the attenuation per unit length. $\Delta\omega=\omega-\omega_0$ is the detuning, where ω_0 is the centre frequency. $t_r=2\pi n_r R/c$ is the round-trip time, where n_r is the effective index and R is the radius of the ring resonator. To obtain the transfer matrix of an n-coupled array, the matrices for each ring are multiplied together:

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = T_1 \cdot T_\phi \cdot T_2 \cdot T_\phi \cdots T_N \begin{bmatrix} c_N \\ d_N \end{bmatrix} \tag{3}$$

Here, T_f is the transfer matrix of the bus lines, given by

$$T_\phi = \begin{bmatrix} e^{j\beta_b L_c} & 0 \\ 0 & e^{-j\beta_b L_c} \end{bmatrix} \tag{4}$$

where b_b is the propagation constant of the bus waveguide. As mentioned before, L_c was adjusted to a multiple of a half-wavelength.

3. DEFINITIONS AND ASSUMPTIONS

Various assumptions were made. Loss in the couplers and bus lines was ignored, chromatic dispersion and polarization were not considered. The resonant frequencies and spacing of the rings were assumed to be equal. The coupling coefficients between the rings and bus lines were assumed not to vary with wavelength. As was explained in the introduction, the spacing between the rings was chosen to be an integral number of half wavelengths.

The centre resonant vacuum wavelength was selected to be an ITU wavelength, 1547.72 nm. The effective indices of the ring and bus were chosen to be 1.6, and assumed to be constant across the operating band of the filter. The ring radius and ring spacing were 298.3 um and 937.3 um, respectively. The ring circumference corresponds to 1938 wavelengths at the resonant frequency, and the free spectral response is 100 GHz.

A common definition of crosstalk for specifying interleavers, used in this paper, is the maximum value of the transmission magnitude for a channel within +/- 10 GHz of an adjacent channel. A typical value of crosstalk according to this definition for a commercial planar waveguide interleaver is -23 dB, at all temperatures. The shape of the passband was characterized according to an arbitrarily defined shape factor, given by the -1 dB bandwidth divided by the -10 dB bandwidth. A typical value for a planar waveguide interleaver is 0.65, and higher shape factor indicates better passband shape.

4. INTERLEAVER DESIGN AND OPTIMIZATION PROCEDURE

For an interleaver, it is important that the filter be insensitive to the exact channel wavelengths, as these can shift in WDM networks due to numerous factors. Therefore the passbands should be box-like, that is, wide and flat. Increasing the coupling coefficients in the array broadens the passbands in the drop port spectrum, however at the price of higher crosstalk. Also, the passbands in the through port spectrum become narrower as coupling coefficients increase. Note that for application to interleaving, labelling of the output ports as through and drop ports is arbitrary, and they ideally have identical spectra, but with different centre wavelengths. Since the spectra in the through and drop ports are not symmetric, it becomes necessary to adjust the coupling coefficients to optimize some parameter applicable to the spectra. This parameter was initially chosen to be -3 dB bandwidth, however equalization of this parameter in the through and drop ports generally results in unacceptable crosstalk in one of these ports. Therefore, the final optimization procedure consisted of minimizing and equalizing crosstalk in the output ports. This procedure resulted in acceptable values for other parameters such as -3 dB bandwidth and shape factor.

Apodization of the coupling coefficients is necessary to achieve low crosstalk. As done previously,[1,4] exponential apodization was used, according to $k_N = A\ \mathrm{Exp}[-a\ (N - N_c)^2]$, where A is the coupling prefactor, a is the apodization coefficient, and N_c is the number of the central ring. In the case of an even number of rings, N_c was taken to be halfway between the centre pair of rings. Unlike previous papers, apodization of both the input and output coupling was done. It will be shown later that unequal coupling between the rings and the bus lines at the input and output causes undesirable notches in the passband of the drop port, and increases crosstalk in the through port. Therefore, input and output coupling was made equal for each ring in the array.

Optimization of the output spectra was done as follows. The power coupling prefactor was varied in increments of 0.5, and the apodization varied in increments of 0.005. For each combination of coupling prefactor and apodization, the crosstalk in the drop and through ports was calculated. The optimal values were those for which the crosstalks in each output port were equal and minimal. Optimal coupling values were obtained for arrays with one through to nine rings.

5. OPTIMAL TRANSMISSION SPECTRA FOR A FOUR-RING ARRAY

The transfer function for a four-ring array, as an example, is shown in Fig. 4. Both the apodized and unapodized cases are presented. It can be seen that apodization produces a significant improvement in side lobe height, and therefore crosstalk, albeit with reduced shape factor. These calculations assumed 10 % dissipative power loss in each ring, however, as will be explained, there is little variation in crosstalk and shape factor for less than 20 % loss.

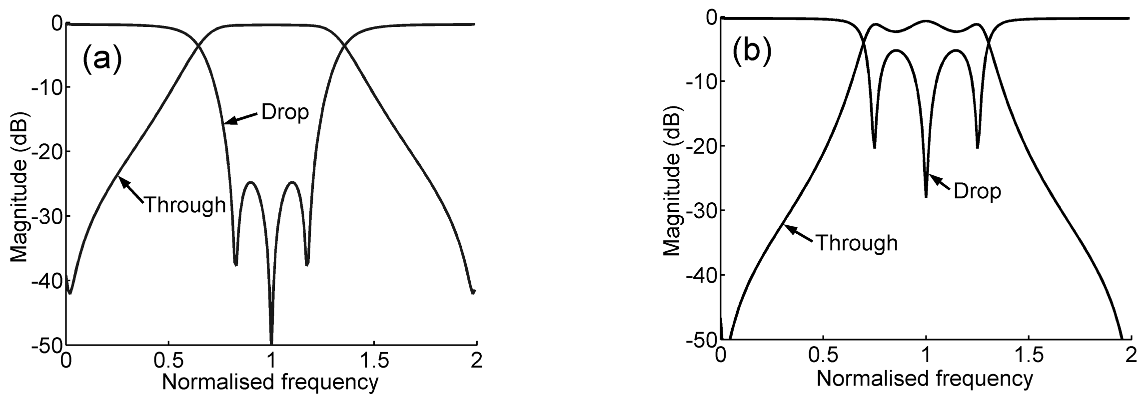

Figure 4. Four-ring array transmission spectrum. (a) With optimal apodisation. (b) With no apodisation.

Fig. 5 illustrates the optimization procedure by presenting graphs of through and drop port spectra for different apodization parameters and coupling prefactors. Crosstalk in the through port remained fairly constant with apodization parameter, and decreased as the coupling prefactor was increased. The crosstalk in the drop port was limited either by the main peak width or the side lobe height. The main peak width determined crosstalk only for high coupling prefactor, and increased for higher apodization parameter. The side lobe height, however, was smaller for higher apodization, and remained fairly constant with coupling prefactor. Therefore, in this case the minimum equal crosstalks in each output port occurred at a coupling prefactor for which the main peak widths in the drop and through ports were equal, and at an apodization value for which the contribution to crosstalk by the side lobe height and main peak width in the drop port were equal.

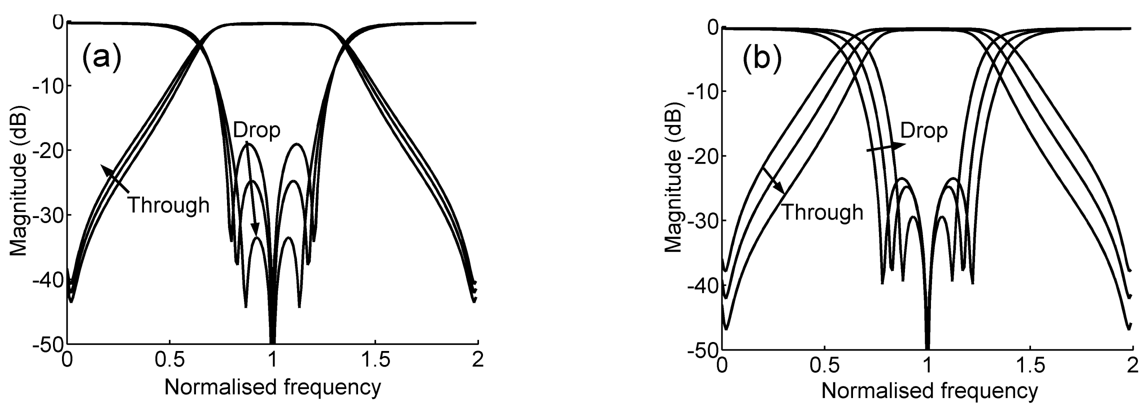

Figure 5. (a) Drop port and through port spectra for 4-ring array for three values of the apodization parameter: 0.1, 0.125, 0.15. (b) Coupling prefactor: 0.6, 0.7, 0.8. The arrows indicate how the curves change for increasing parameter values.

6. OPTIMAL PARAMETER VALUES FOR VARYING RING NUMBERS

Graphs of optimal values of various parameters are given in Fig. 6 for varying numbers of rings in an array. As can be seen, crosstalk and shape factor improve as more rings are added. Crosstalk plateaus for between four and seven rings.

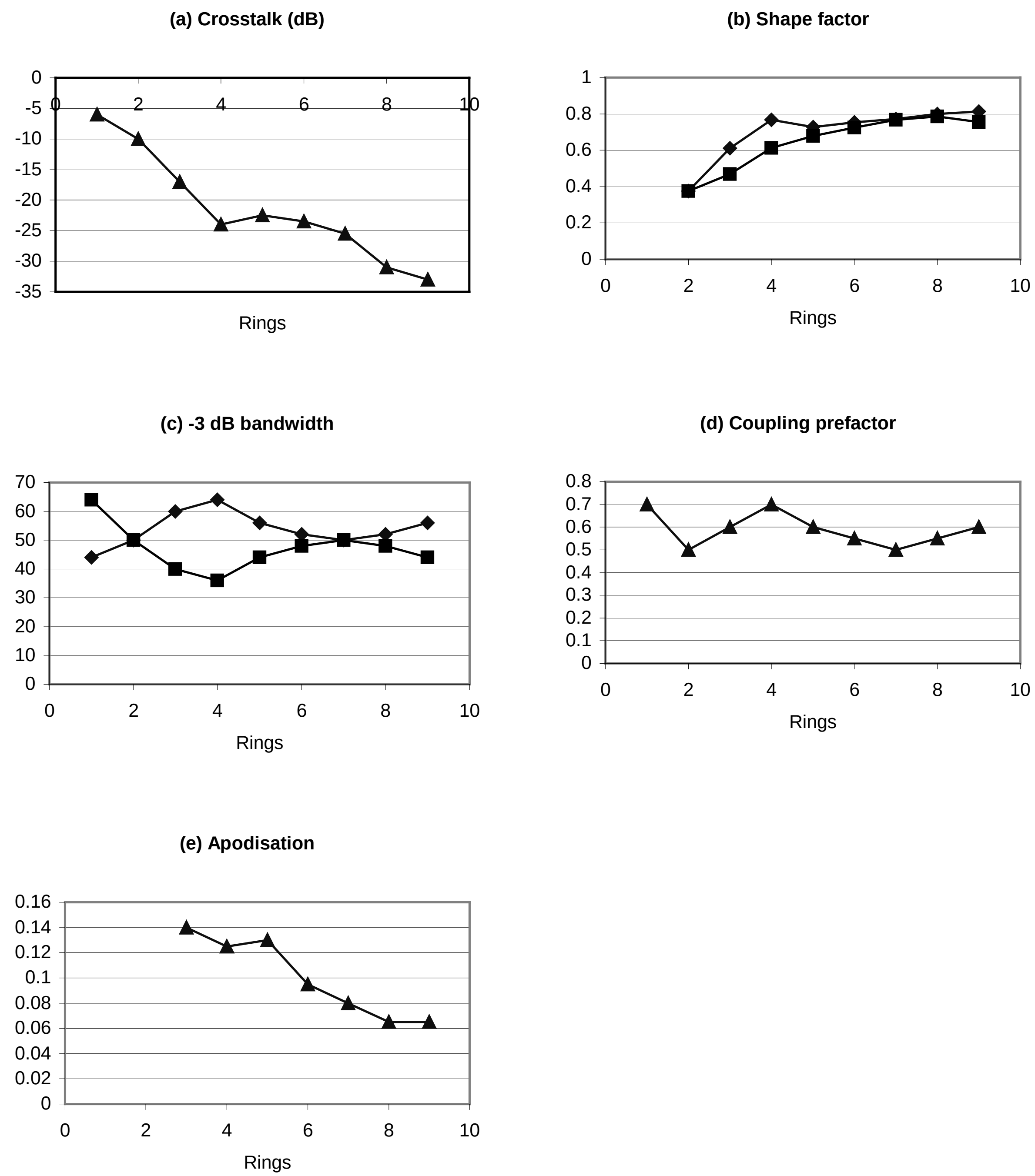

Figure 6. Optimal parameter values versus numbers of rings for parallel-coupled array. Diamond symbols denote the drop port, squares the through port, and triangles both ports.

Fig. 6 can be used to determine the optimal number of rings in an array. The choice will depend on whether the performance parameters meet commercial specifications. For commercial integrated-optic interleavers, crosstalk is often specified as <-22 dB at +/- 10 GHz from an adjacent channel. A four-ring parallel array meets this specification, as Fig. 6(a) shows. For less than eight rings, there is little benefit in increasing the number of rings due to the plateau in this graph. A shape factor of 0.65 is typical for a commercial interleaver. A four-ring array achieves an acceptable shape factor of 0.61. A parameter of lesser importance is the -3 dB bandwidth. This is typically 50 GHz for a commercial device. As Fig. 6(c) shows, the -3 dB bandwidths of the drop and through ports of a four-ring array are 64 GHz and 36 GHz respectively. Although the -3 dB bandwidth of the through port is low, the shape factor is still good.

7. THE EFFECT OF LOSS ON TRANSMISSION SPECTRA

Insertion loss, or the magnitude of the transmission spectrum at resonance, is plotted in Fig. 7(a) for both the through and drop ports as a function of dissipative loss. Here, the dissipative loss is defined as the power loss in an isolated ring for a complete round-trip, and may be due to bend loss, scattering due to sidewall roughness, and absorption. As the figure shows, insertion loss exceeds 1 dB for dissipative loss greater than ~20 %. Fig. 7(b) shows that crosstalk is only significantly affected for dissipative loss greater than 40 %. Thus, losses of up to 20 % can be tolerated.

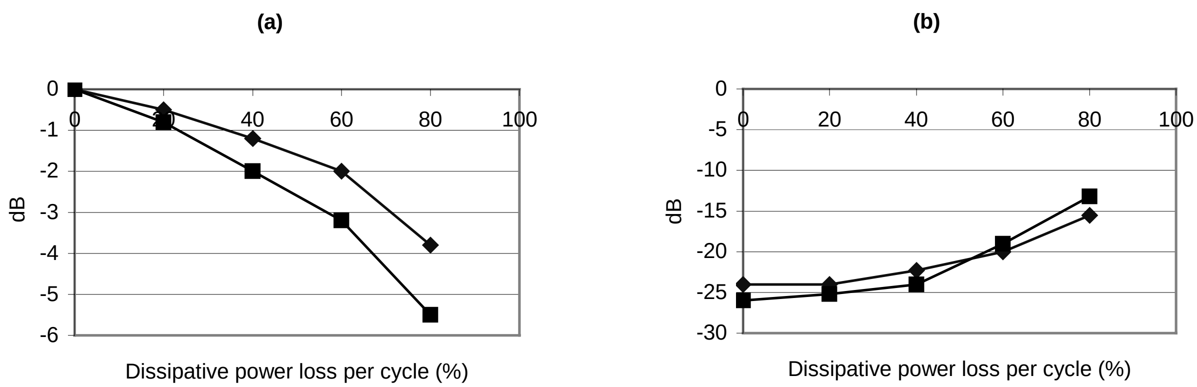

Figure 7. The effect of dissipative loss on (a) insertion loss at resonance and (b) crosstalk for a four-ring array. Diamond symbols denote the drop port and squares the through port

8. CRITICAL CONDITIONS ON COUPLING

Balancing the coupling coefficients between the rings at the input and output bus lines is a critical problem for parallel-coupled arrays. It can be shown that there are several overlapping poles and zeros in the drop spectrum at the resonant frequency for the drop port. If the coupling at the output is less than that of the input, for example, the poles move away from the centre frequency so that they no longer overlap the zeros. The result is that the passband is no longer flat. This is illustrated in Fig. 8 for a large difference in coupling prefactors. Although the notches in the magnitude are only a few dB, it should be noted that the effect on chromatic dispersion is large, as will be discussed in a subsequent paper. Therefore, balancing the input and output coupling coefficients is critical.

9. FEASIBILITY OF A PARALLEL-COUPLED ARRAY FILTER

It is important to minimise the number of rings in an array to simplify the problem of tuning the array. In an actual device the phase length of the bus lines connecting the rings must be tuned so that the signals from each ring have the correct phase relationship. Furthermore, the resonant frequencies of the rings must be tuned. The task of tuning is difficult since only the signals from the drop and through ports are accessible, and the spectra become more complex as rings are added to the array. Therefore, minimizing the number of rings in the array simplifies the tuning procedure. The optimal number of rings in the array is the minimum number for which crosstalk and shape factor are acceptable, which is four rings, according to Fig. 6(a) and Fig. 6(b).

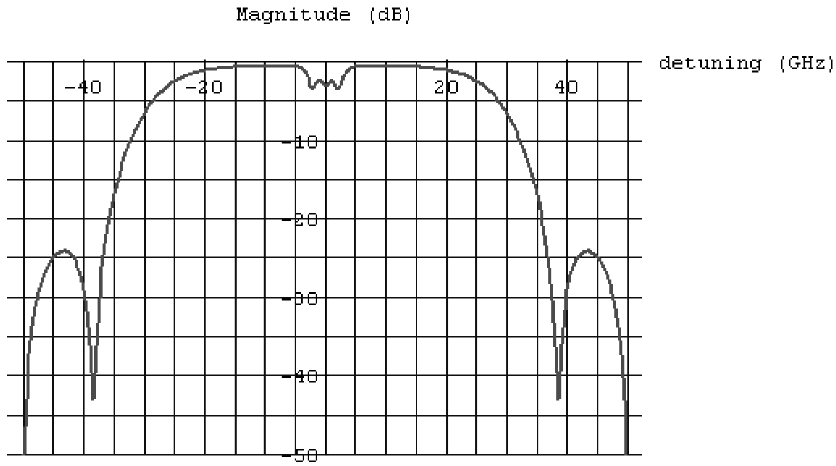

Figure 8. Drop port transmission spectrum for coupling prefactors of 0.7 at the input and 0.4 at the output

In addition to tuning, the feasibility of producing a parallel-coupled ring array is dependent on whether the dissipative loss in the rings is acceptably small. Current research has focused on demonstrating low-loss microrings.[6] Microrings use high-index materials such as Si and SiN to achieve low bending loss. Also, their small size minimizes scattering loss, since although the scattering loss per unit length is high the circumference, and therefore overall scattering loss, is small. This type of ring is ideal for single-channel drop filters. Interleavers, however, require large rings due to their smaller free spectral response. The ring radius employed in this paper was 298.36 um. For this ring size high index contrast materials are not desirable due to high scattering loss, however use of lower index material results in increased bending loss. Fortunately, the parallel-ring interleaver design is tolerant of high dissipative losses in the rings. As calculated earlier, 20 % dissipative loss can be tolerated. The high tolerance to losses in the rings is a consequence of the high ring-bus coupling coefficients. Therefore, large coupling of light from the input bus compensates dissipative losses in the rings, and coupling to the buses is the primary determinant of the width of the passband.

The primary advantage of a parallel-coupled ring resonator filter is its small area. The area occupied by the waveguides of a four ring array is roughly 3.4 mm x 0.6 mm, compared to a state-of-the-art compactly folded MZI interleaver[7] with area 4.2 cm x 2 cm. The small area of the ring array enables it to be more easily integrated with other devices on a wafer, such as array waveguide gratings.

Another type of filter suitable for interleaving is an MZI with a ring resonator coupled to one arm. This device approaches the parallel ring array in size, but requires splitters with accurate splitting ratio. Such a device was produced using SiON technology and had an area of around 5 mm x 2.5 mm.[8] The simulated crosstalk of this filter was –30 dB, superior to the filter design presented in this paper, however this was not achieved due to non-ideal splitting ratios in the MZI couplers. A design that overcomes this problem has tunable splitters.[9] This device, which was 19 mm x 5 mm, had crosstalk of –15 dB that was limited by non-ideal ring-waveguide coupling coefficient and polarization dependence. Another MZI/ring filter was described by Melloni et al.[10] and was also produced using SiON technology. Although good crosstalk and passband flatness was achieved in the through port spectrum, the drop port spectrum was poor due to asymmetry from losses and phase shifts in the ring coupler. A major advantage of this filter, however, was polarization independence, which was achieved by using ridge waveguides designed so that the form birefringence cancels the material birefringence. Another MZI/ring resonator interleaver has been fabricated using InGaAsP technology.[11] Good balance in the through and cross port spectra was obtained by using MMI couplers rather than directional couplers to improve the accuracy of the splitting ratio. Crosstalk was limited to –17 dB by power mismatch between the two arms of the MZI, and insertion loss was limited to –11 dB by fibre coupling losses.

10. CONCLUSION

We have shown that a parallel-coupled array achieves performance comparable to commercial planar waveguide interleaving filters in terms of magnitude response, and that four rings is the best choice for array size. A 50 - 100 GHz deinterleaver can theoretically attain a crosstalk of -24 dB, insertion loss of <1 dB, and shape factor >0.6. Apodization of the coupling coefficients was shown to be necessary to minimise crosstalk, and equalization of the input and output coupling coefficients critical for correct operation of the filter.

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