Analysis of the Resonant Wavelength Router

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The Wavelength Resonant Router (λ-ReR) is an optical integrated crossbar matrix based on ring resonators. The λ-ReR is similar but more flexible than an AWG. Both the spectral characteristic and the impact on WDM systems are investigated.

Keywords: integrated optics, ring resonator, optical filter, router, Bit Error Rate

Introduction

In the last years ring resonators attracted the attention of many researchers, mainly thanks to the selective frequency response, the small dimensions and because they can be exploited as the main building block of an add-drop, a de-multiplexer or even a crossbar matrix. In this contribution the integrated optic crossbar matrix based on ring resonators, named *Resonant Router (*ReR) and shown in Fig. 1, is described and its application as wavelength router (λ-ReR) is investigated. The nodes characteristics are described and the routing performance in terms of Q, extinction ratio and BER are discussed. An effective method for the estimation of the impact on BER is also presented. Preliminary experimental results on a single node realized with one ring conclude the contribution.

The wavelength resonant Router (λ-ReR)

The ReR can be exploited either as a Cross Connect or as a λ-Router, depending on the FSR of each node respect to the channel spacing of the WDM system. The characteristics of the ReR in the Cross Connect configuration have been already investigated in Ref. [3] and here we focus on the λ-Router function. As shown in Fig. 1 this device consists in a crossbar matrix with N inputs and N outputs each one carrying N wavelengths, forming a grid of $N \times N$ straight waveguides with $N \times N$ nodes. In each node one or more rings connect the two crossing waveguides. A single ring is often sufficient but the transfer function of each node can be improved by cascading two or more rings per node, as shown in Fig. 1a) and 1b).

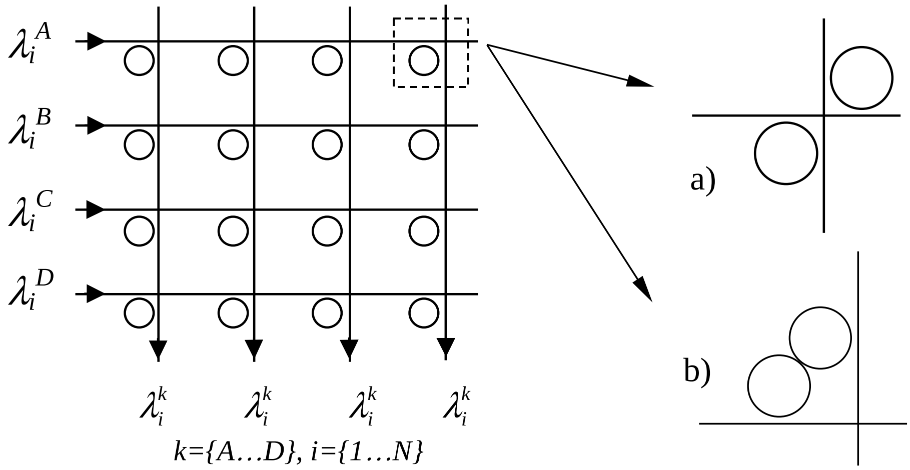

Fig. 1 – Structure of a 4×4 λ-ReR. Node with a) two rings in parallel and b) with two rings in series.

The FSR of each node must be at least equal to the channel spacing multiplied by the number of channels. Each node redirects the input channel at wavelength λ_i to the output vertical waveguide if

λ_i is the resonating wavelength of the node itself. Instead, if λ_i do not resonate, the signal propagates unaffected toward the next node. The ReR can be fully reconfigurable by tuning the resonant frequency of the rings, for example, with small thermo-controllers placed over the rings. An important feature of the ReR is that only one resonating node is encountered in the input/output optical path, reducing at maximum the filtering impairments and the insertion losses.

As an example, let's consider a λ-Router with a FSR=400 GHz and dimension N=8. The ReR is suitable for a 8-channels WDM system with channel spacing of 50 GHz but it can be used also in systems with a smaller number of channels. The input/output transfer function shown in Fig. 2 refers to a ReR with two rings per node. The nulls in the transmission transfer function are present only if at that wavelength a resonant ring is encountered on the input/output path. The in-band spectral behaviour depends mainly on the characteristics of the single node that must be accurately designed to avoid group delay distortions, losses, intersymbolic interference (ISI), cross talk, and dispersion impairments [2]. The ISI affects the shape of the pulses and is due to the filtering properties of the resonant nodes. The out-of-band behaviour, instead, depends also on the input/output path.

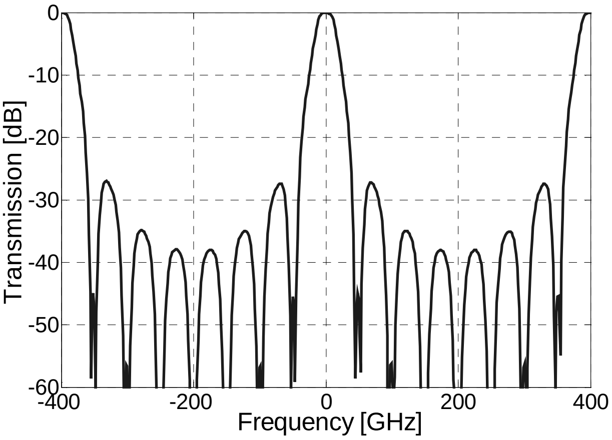

Fig. 2–Typical transfer function of a λ-ReR with N=8, FSR=400 GHz and two rings per node.

BER Estimation Method

Because of the presence of ISI and cross talk, the Q-factor and the Bit Error Rate (BER) of a system that includes a ReR cannot be calculated from the eye diagram as usual. The method used to estimate the ReR impact on the BER is shown in Fig. 3. An Additive White Gaussian Noise (AWGN) is added to the input sequence s. Then, passing through the matrix, the noisy sequence is filtered by the resonant node with transfer function H_{21} and by all the others non resonant nodes H_{11}. This operation introduces losses, distortion and an additive intersymbolic interference term i. Moreover, if N is the matrix dimension, $N-1$ cross talk contributions x are added to the filtered sequence. The cross talk signals are considered incoherent with the considered channel, so their powers are added to the power of the reference sequence to obtain the output sequence. Finally, the receiver discriminates the bits 1 and 0 by mean of an optimum threshold t that minimizes the BER.

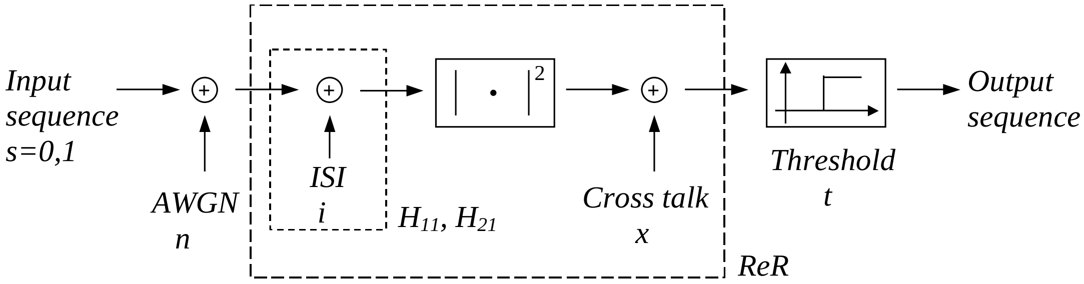

Fig. 3 – Model used to estimate the ReR impact on the BER.

The BER is estimated assuming that when the transmitted bit is 0, an error is obtained when $|s+n|^2+x>t$, that is when $n > \sqrt{t-x} - s$. The BER conditioned to the transmission of the bit 0 is

$$P(\varepsilon \mid 0) = BER0 = \sum_i \sum_x \frac{1}{2} erfc\left(\frac{\sqrt{t-x} - s}{\sigma_n \sqrt{2}} \right) P(i) P(x), \tag{1}$$

where σ_n is the standard deviation of the noise in the output sequence, and *P(i), P(x)* are the distribution of ISI and cross talk respectively. In the same way, the error probability conditioned to the transmission of bit 1 is found as

$$P(\varepsilon \mid 1) = BER1 = \sum_i \sum_x \frac{1}{2} erfc\left(\frac{1 + s - \sqrt{t - x}}{\sigma_n \sqrt{2}} \right) P(i) P(x). \tag{2}$$

The final Bit Error Rate is then the average between *BER1* and *BER0* and the *Q*- factor can be derived from the calculated BER:

$$BER = \frac{BER0 + BER1}{2} = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}} \right). \tag{3}$$

λ-ReR System Performance

In this section we analyse the impact of a λ-ReR with FSR=400 GHz on a 10 Gbit/s NRZ system. Three cases have been considered: 4 channels spaced by 100 GHz (*N=4*); 8 channels spaced 50 GHz (*N=8*) and 16 channels spaced 25 GHz (*N=16*). An unfiltered slightly noisy input sequence formed by supergaussian pulses (*m=2*) is used.

The design of the nodes consists in the determination of their bandwidth as a function of the bit rate, the modulation format and number of the WDM channels, the maximum achievable FSR being imposed by the available technology. In Fig. 4a) and b) the Extinction Ratio and the *Q*-Factor versus the bandwidth *B* at –3 dB for a single-ring based λ-ReR is shown. The same analysis was performed for λ-ReR with two rings in series and in parallel per node but we have found that the single-ring structure is sufficient to handle the three considered systems. Two or three rings are required only by systems with a higher spectral efficiency.

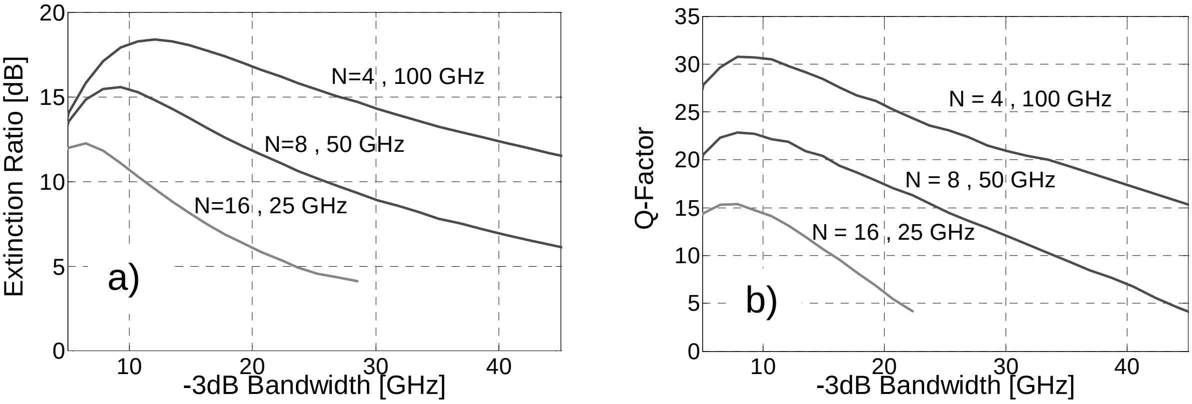

Fig. 4 – Extinction Ratio (a) and Q-Factor (b) versus the node bandwidth of the λ-ReR *used in three different 10 Gbit/s WDM systems. Each node consists in a single ring.*

The signal routed by the λ-ReR is affected by ISI and, in the worst operating conditions, by *N-1* cross talk signals. Nodes with a large bandwidth ensure a negligible pulse distortion and ISI but present a poor out-band extinction ratio and hence a high cross talk level. The reduction of the cross talk is achieved by increasing the node selectivity but this increases pulse distortion and hence ISI. The trade off between the two impairments leads to the optimum node bandwidth clearly evident from the graph shown in Fig. 4a) and 4b): in the considered cases we found that a bandwidth between 8 and 9 GHz is a good compromise that optimize the performance of the λ-ReR.

Below 9 GHz the λ-ReR is limited by ISI and above by cross talk. In general, with the optimal *B* the performance of the device are strictly dependent on the spectral efficiency of the system that is on the ratio between the bit rate (or the required bandwidth *B*) and the channel spacing. Moreover, it results that, to a first order and for a given channel spacing, the optimum bandwidth and the achievable system Q-factor do not depend on the matrix dimensions or the number of channels *N*.

The calculated output eye diagrams obtained from a λ-ReR with B=9 GHz for N=4 (100 GHz spaced) and N=16 (25 GHz spaced) are shown in Fig. 5. Comparing Fig. 5a) and b) it appears that the pulse shape is almost the same because the distortion depends only on the node bandwidth. Instead, the cross talk level is much higher in the 16-channels WDM system (Fig. 5b), affected by 15 contributions, respect to the N=4 case that is affected by only 3 contributions. Note that the sequence shown in Fig. 5b) can be considered error-free even if its extinction ratio is only 12 dB.

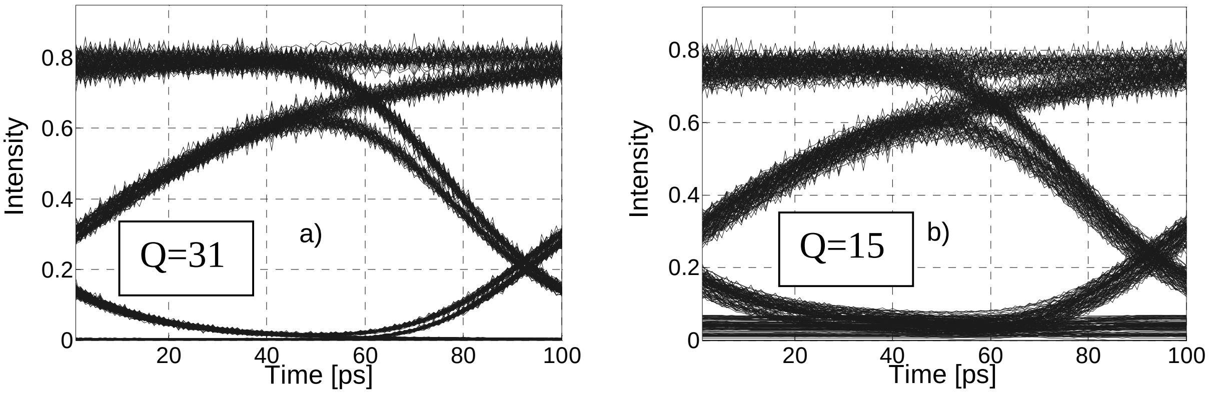

Fig. 5 –Eye Diagrams of the 10 Gbit/s output sequence from a 4×4, 100 GHz and 16×16, 25 GHz spaced λ-ReR. Each node consists in a single resonant ring with FSR=400 GHz.

To check the feasibility of a ReR, several switching nodes based on single and double ring resonator have been realized by using SiON technology with an index contrast Δn≈6% (LioniX BV [4]). This index contrast allows a bend radius of about 300 μm, providing a FSR of 100 GHz. A FSR=400 GHz should be achievable with a slightly higher Δn (8%). By using different coupling coefficients we have obtained bandwidth from 3.75 to 12.5 GHz and out-band extinction ratios from 25 to 14 dB. Two examples of the measured transfer function 'fiber-to-fiber' are reported in Fig. 6. According to the results of our simulations, these spectral characteristics are sufficient for the implementation of a 4×4 λ-ReR with channel spacing of 25 GHz.

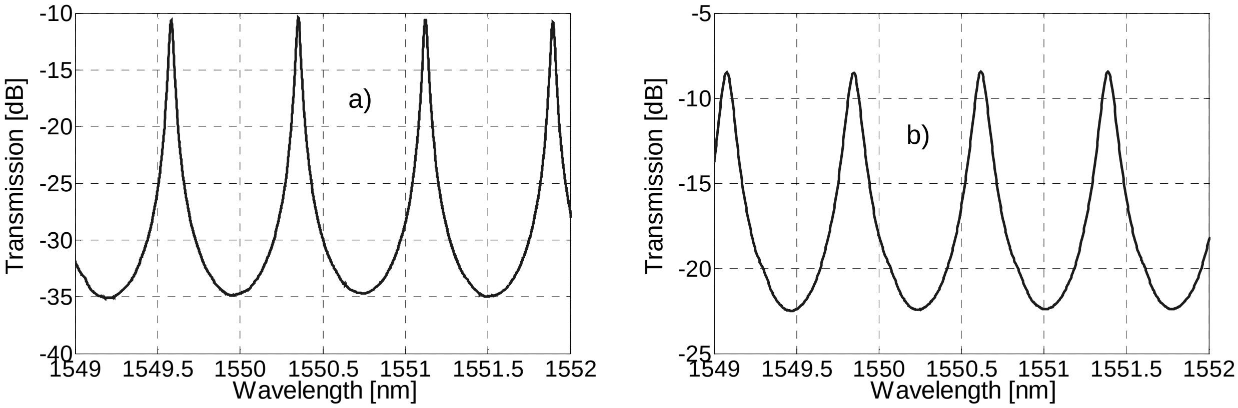

Fig. 6 – Measured transfer function of two single-ring resonators with a) bandwidth of 3.75 GHz and extinction ratio of 25 dB b) bandwidth of 12.5 GHz and extinction ratio of 14 dB.

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