Experimental evaluation of ring resonator filters impact on the bit error rate in non return to zero transmission systems

A. Melloni and M. Martinelli
Dipartimento di Elettronica e Informazione, Politecnico di Milano, via Ponzio 34/5, Milano 20133, Italy
melloni, martinelli @elet.polimi.it

G. Cusmai and R. Siano
CoreCom, via G. Colombo, 81, Milano 20133, Italy
cusmai,siano@corecom.it

Abstract: The paper discusses an experimental investigation of the impact of a single ring resonator and a double ring resonator filter on the performance of an optical communication Non Return to Zero system at 2.5 Gbit/s and 10 Gbit/s. Bit Error Rate curves are reported and discussed. Experiments demonstrate that filtering and routing channels of dense wavelength division multiplexed systems is possible and advantageous with ring resonator filters.

Keywords: Resonators; Integrated optics Devices; Optical Communications systems.

1. Introduction

Ring resonators based filters with spectral characteristics and insertion losses suitable to satisfy the tight requirements of modern Dense Wavelength Division Multiplexed (*DWDM*) systems have been recently published [1, 2]. These devices possess the desired characteristics, flat in band response and high rejection in the stop band, for filtering, packing, separating, routing and managing large numbers of closely spaced channels and could be the key elements to increase the spectral efficiency of *WDM* systems [3 - 5].
The aim of this work is to begin to investigate ring-based filters from the system point of view [6, 7]. In this paper we report, for the first time to our knowledge, an experimental evaluation of the impact of a single ring resonator and a double ring resonator filter on the performance of an optical communication system. In particular, we study the impact of both the intensity and the group delay transfer function shape of ring resonator filters on intensity-modulated Non Return to Zero (*NRZ*) single-channel at *2.5 Gbit/s* and *10 Gbit/s* through measurements the Bit Error Rate (*BER*). In principle, a small filter bandwidth is useful to clean up the signals from the optical noise and to reduce the spectral width of modulated signals but at the expense of pulse distortion, intersymbolic interference (*ISI*) and a penalty on the *BER*. In this work we demonstrate that ring-based filters can be advantageously exploited to achieve channel spacing of *12.5 GHz* in *10 Gbit/s* systems with a low power penalty.
Section 2 reports a synthetic description of the filters, Section 3 describes the set-up used for the *BER* measurements and Section 4 discusses the experimental results.

2. Ring resonator based filters

In this study two kind of filters are considered: a single ring-resonator bandpass filter and a double direct-coupled ring-resonator filter [3]. The single ring filter, with the ports definitions, is schematically shown in Fig. 1a). At resonance the input signal is guided to the drop port, out of resonance it passes straight to the through port. The typical ideal periodic spectral response at the drop port is reported in Fig. 1b). The period of the transfer function or Free Spectral Range (*FSR*) is inversely proportional to the ring group optical length $n_g L_r$, where n_g is the group refractive index and L_r is the ring geometrical length. Resonance frequencies f_0, spaced by a *FSR*, depend on the ring phase optical length $n_{eff} L_r$, where n_{eff} is the effective refractive index. The through port presents a complementary transfer function respect to the drop port with a deep notch at the resonance frequencies. In Fig. 1b) the filter bandwidth definitions used throughout the paper are shown. Losses do not affect the shape of the spectral response but simply induce an insertion loss usually higher at the drop port than at the through port. Double direct-coupled ring-resonator filters present a flatter in band transfer function with a wider bandwidth at *–1 dB* and a higher extinction ratio for the same *–3 dB* bandwidth value.

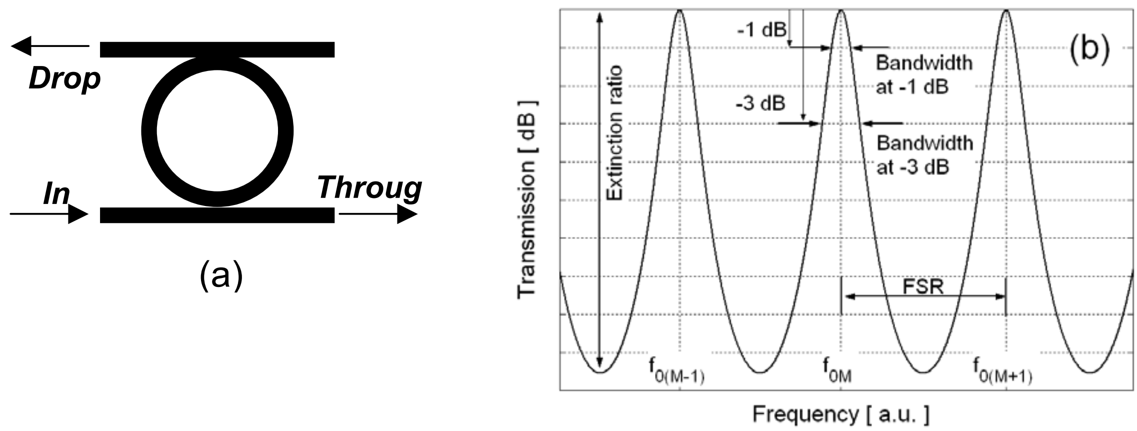

Fig.1. *(a) Ports definition in a single resonator ring filter. (b) Typical single-ring drop port transfer function.*

A sketch of both filters is reported in the inset of Fig. 2. The integrated optic filters have been realized by using silicon oxinitride (SiON) technology [8, 9] with an index contrast between the core and the upper cladding/substrate equal to $\Delta n=6\%$ [1]. SiON is among the most promising materials to obtain such an index contrast, allowing minimum bending radii of $100\ \mu m$ (corresponding to a free spectral range *FSR=300 GHz*) or even lower, with negligible radiation losses and a satisfactory fiber to waveguide coupling efficiency. In our case, the measured ring waveguide attenuation is *0.4 dB/cm* and the fiber to waveguide coupling loss is equal to *0.7 dB* per facet.

The measured spectral responses at the drop port of both filters are reported in Fig. 2. The intensity transmission characteristic has been measured by means of a tunable laser source and

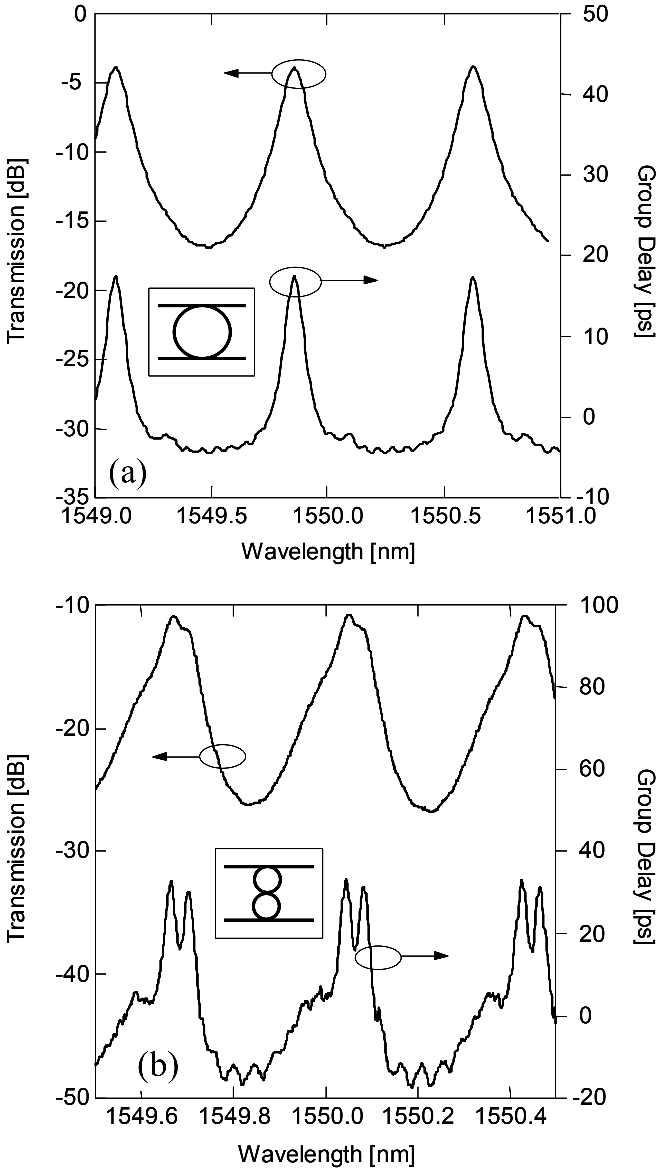

Fig. 2. *Intensity and group delay characteristics of (a) the single and (b) the double ring-resonator.*

an optical spectrum analyser, while the group delay response has been derived by Hilbert inverse transforming the measured spectral response. This procedure is correct and very accurate because of the minimum phase behaviour of this type of filter [1, 4].

The single ring has a radius of *312 μm,* a *FSR* equal to *100 GHz*, a bandwidth at *–1 dB* of *6.25 GHz* (*13.3 GHz* at *–3dB*) and an extinction ratio of *13.5 dB*. The fiber-to-fiber insertion loss is *4.4 dB* for the drop port and only *2.1 dB* for the through port. The experimental double-ring filter spectral response is shown in Fig. 2b). Both rings have a radius of *570 μm*, the *FSR* is *50 GHz*, the bandwidth at *–1 dB* is *7.4 GHz* and the extinction ratio is roughly the same of the single ring.

This filter possesses a small in-band ripple of *0.5 dB* and a very weak polarization dependence. A detailed description of both filters is reported in [1].
The effect of the selective intensity transfer function is mainly to reduce the signal spectral width and to increase the temporal pulse width with subsequent increase of the *ISI*. Even more important is the effect of the group delay characteristic. For the single ring filter the group delay has a bell-shaped characteristic centred at the resonance frequency, whereas for double or higher order filters it is typically flat around the center frequency and increases toward the band edges, as shown in Fig. 2. The filter induced second order dispersion vanishes at the center frequency whereas a third order dispersion is always present and is equal to $1.7\cdot10^4$ ps^3 and $0.5\cdot10^4$ ps^3, respectively for the single and the double ring filter. For this reason the signal spectrum should be centred and well confined inside the filter bandwidth, otherwise the third order dispersion produces an asymmetrical distortion of the pulses. This impairment, however, can be overcome by cascading an all-pass filter to equalize the group delay distortion [4].

3. Experimental set-up

In order to investigate the penalty introduced by the filters, the experimental system set-up shown in Fig. 3 has been used. The performances of the system in back-to-back configuration

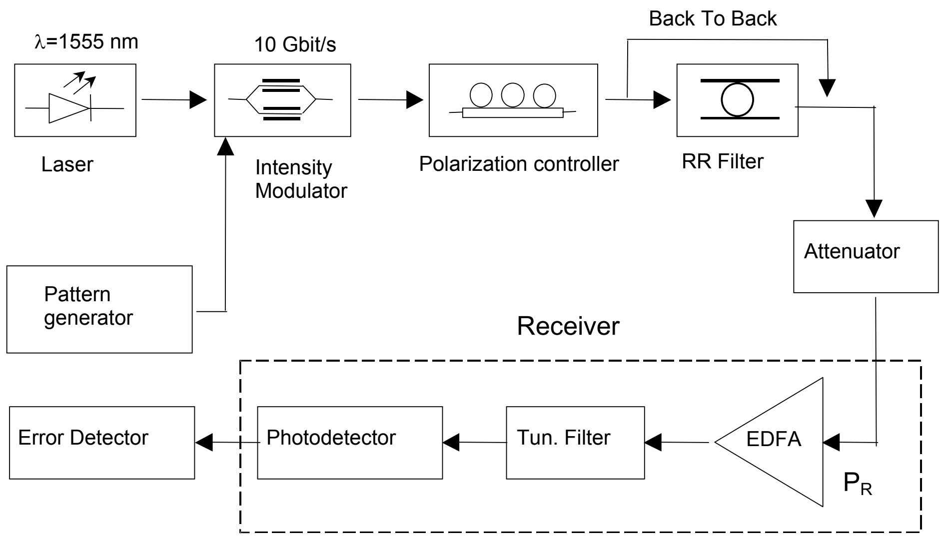

Fig. 3. *Experimental set-up. P_R is the received power.*

(with no filter present) are compared with the performances of the system when the filter is inserted. Neither long distance propagation nor in-line amplification are included in the set-up because the aim is to study the impact of the filter without any other additional effect. Our system comprises a *10 Gbit/s* pattern generator, a transmitter with an external $LiNbO_3$ intensity modulator, a polarization controller, the ring resonator filter (*RR*) under test, a variable attenuator, the receiver block and an Error Detector Unit. The receiver comprises an EDFA preamplifier, a tuneable filter with a bandwidth of *1 nm* and the photodetector with an electrical bandwidth of *17 GHz*. The filter is mounted on a Peltier thermoelectric module with a thermo-

controller that stabilizes the temperature and permits to tune the filters' response to the signal wavelength. The frequency shift induced by the thermal tuning is 1.33 GHz/°C.
The considered set-up is suitable to investigate the pulse shape distortion and the *ISI* induced by the filter and its impact on the *BER*. The *RR* filter inserted before the receiver can be considered either as an optical transmitter filter, such as multiplexers or band limiting filters, as a ring-based device for routing, add and drop and clean up *WDM* channels or as a receiver filter such as interleavers or demultiplexers. The ability to filter the background optical noise is evident from the spectral behaviours reported in Fig. 2a) and 2b) and it is the subject of experiments planned in a short future.

4. Experimental results

The filters have been tested with *NRZ* signals at *2.5 Gbit/s* and *10 Gbit/s*. In these experiments a $2^{31}-1$ long *PRBS* intensity-modulated *NRZ* sequence tuned to the central frequency of the filters has been used. Fig. 4 shows the eye diagrams at *2.5* and *10 Gbit/s* measured in the *Back-To-Back* condition (a), with the single ring (b) and the double ring (c) filter inserted as indicated in Fig. 3.
In the *2.5 Gbit/s* experiment (first column in Fig. 4), the eye diagrams obtained with both filters reveal only a small degradation of the pulse shape. This was predictable because their bandwidth is greater than the bandwidth of the modulating signal. The rounded, slightly asymmetrical pulse shape obtained with the single ring is an effect of the group delay characteristic that, at the center frequency, shows a negligible second order dispersion and a small third order dispersion, as can be noted from Fig. 2. A further effect of the group delay characteristic is the shift of the cross point towards the zero level, affecting the choice of the optimum threshold level of the receiver. The distortion disappears with the double ring filter because of the slightly wider bandwidth and the smaller third order dispersion.

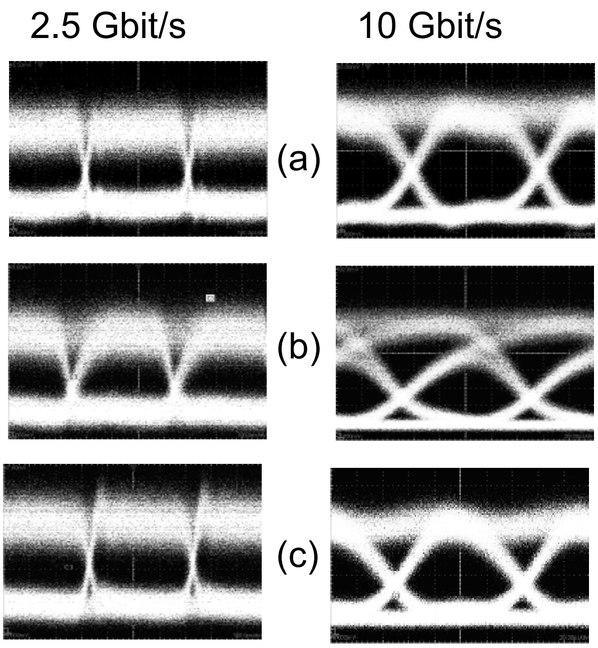

Fig. 4. *2.5 Gbit/s and 10 Gbit/s NRZ eye diagrams of (a) the Back to Back, (b) the single-ring filtered and (c) the double ring filtered sequence.*

A beneficial effect provided by these selective filters is the spectrum cleanup from the optical noise, leading to an improvement of the *BER* performance of the system. The measured *BER* curves versus the received power P_R are shown in Fig. 5a) for the three considered conditions at *2.5 Gbit/s*. Both filters induce a negative power penalty, that is an improvement of the *BER*. Note that the slope of the linear interpolating lines of the three *BER* measured data remains unchanged, meaning that the *ISI* contribution is negligible. By using the double ring filter, a *BER* of 10^{-9} is obtained with a received power of only *–35.6 dBm*, whereas the back to back condition requires P_R=*–34 dBm*. An even higher improvement is expected when EDFAs are inserted before the filter, as in amplified links.

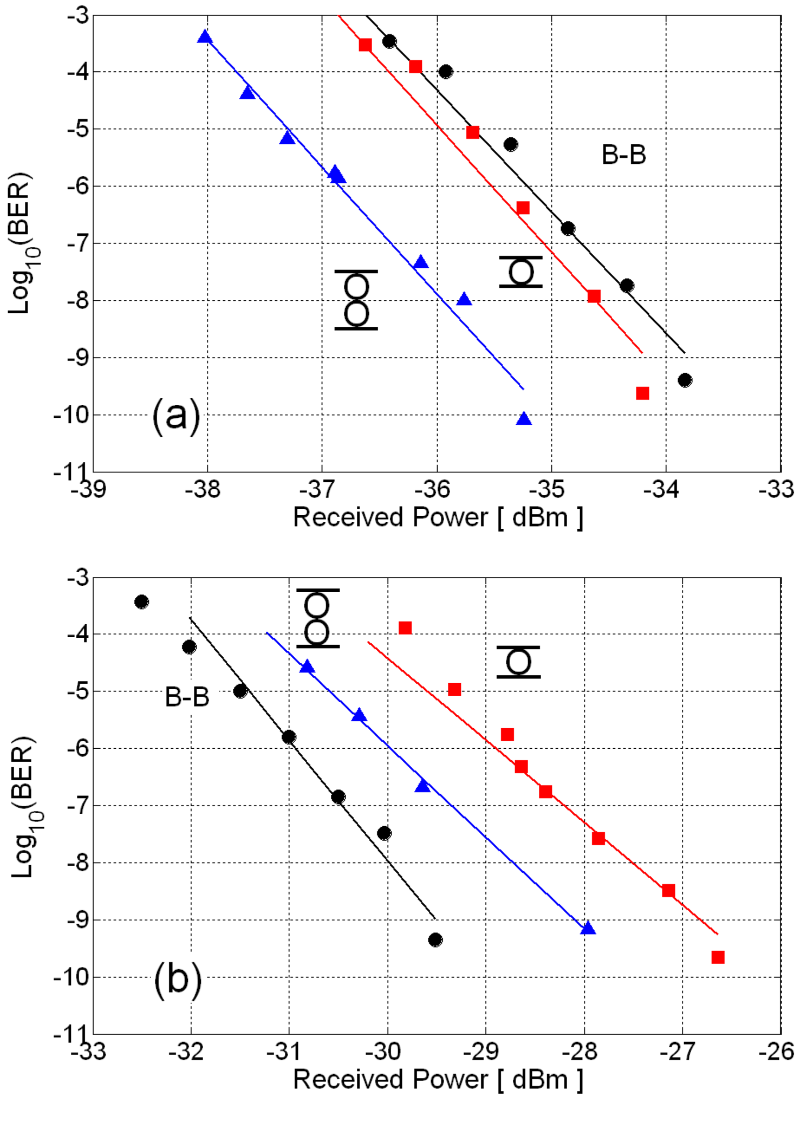

Fig. 5. *BER of NRZ transmission at (a) 2.5 Gbit/s and (b) 10 Gbit/s (● Back to Back; —■—Single ring; —▲— Double ring).*

For both filters, the *BER* has been measured also in the through condition, that is when the rings do not resonate at the signal wavelength and the sequence is directed to the through port, unaffected. In both cases, the impact of the filters is absolutely negligible and the *BER* curves

overlap the back-to-back one. In this condition, in fact, both the intensity and the group delay spectral behaviour are flat and do not affect the pulses shape.
In the *10 Gbit/s* experiment, the filtering effect is more pronounced, being the bandwidth of the signals comparable or even greater than the bandwidth of the filters. In this case, especially with the single-ring device, the eye diagrams shown in the second column of Fig. 4 reveal asymmetrical pulse distortion and *ISI*. The single ring induces an evident *ISI*, the slope of both pulses' edges is reduced and the eye closes. Also in this case the group delay characteristic induces an asymmetric deformation and shifts the crossing point toward the zero level. The double ring filter, instead, thanks to the flatness of the bandpass characteristic, produces a more open eye and induces a small power penalty. The asymmetry has almost disappeared, too.
The *BER* curves versus P_R, measured at *10 Gbit/s*, are reported in Fig. 5b). For a *BER* equal to 10^{-9} the induced power penalty is *2.2 dB* and *1.3 dB* for the single and the double ring filter, respectively. In this case, the slope is slightly lower because of the *ISI* impairment. An even lower penalty is expected for a higher order filter or a filter with an in-band flat group delay characteristic [4]. A null power penalty has been measured in the through configuration, as for the *2.5 Gbit/s* case.

5. Conclusions

In this article we have reported the results of an experimental investigation on the impact of ring-based filters on the *BER* of a NRZ optical communication system. Although further investigations must be carried out, especially inserting a propagation link and optical amplifiers before or after the filter, inserting adjacent modulated channels, detuning the filters respect the signal wavelength and so on, this experiments demonstrate that ring resonators based filters are potential candidates for the realization of high performance devices for *DWDM* systems. In particular, they can be exploited to increase the spectral efficiency of *DWDM* systems where a channel spacing of *12.5 GHz* with bit rates of *10 Gbit/*s can be achieved with a low power penalty.

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