160-Gb/s Optical OFDM Demultiplexer based on Photonic Ring Resonators

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Abstract— **A novel all-optical OFDM demultiplexer based on integrated photonic ring resonators (RR) is proposed and its performance validated. The proposed optical OFDM demultiplexer overcome the processing speed limits introduced by electronics and is suitable for very large scale integration, providing a compact and cost-effective solution. The performance of this device considering a Silicon-on-Insulator (SOI) platform has been demonstrated by demultiplexing a 160-Gb/s (4-subcarrier x 40-Gb/s) OFDM signal. Simulations results show excellent BER performance with error-free operation for each demultiplexed subchannel.**

Keywords: Optical Frequency Division Multiplexing (OFDM); Ring Resonators (RR); Integrated Photonic devices

I. INTRODUCTION

High-speed optical transmission technologies are the key to construct cost-effective optical transport networks (OTNs). Optical orthogonal frequency division multiplexing (OOFDM) has become a promising technique in long-haul and high-speed optical transmission systems, for its high spectral efficiency, and advanced robustness against chromatic dispersion and polarization mode dispersion [1]. The concept underlying OOFDM is the generation of analog symbol signal (OFDM channel), whose spectral components include multiple subcarriers modulated in parallel by independent data streams with relatively low rates. All the subcarriers are orthogonal to each other so that their spectra overlap, which makes subchannel extraction by means of conventional optical bandpass filtering impossible. As a consequence, only appropriate receivers are able to demultiplex OOFDM signals. These receivers are based on fast Fourier Transform (FFT) processing [2].

Most of existing OOFDM systems perform the FFT on the time-sampled signal in the electronic domain. Such electronic real-time implementations are currently restricted to OFDM symbol rates of a few GBd due to speed limitations of the digital signal processor. Moreover, as higher bit rates are needed (core channel bitrates are expected to operate at 100 Gbit/s and up to 1 Tbit/s), electronic processing becomes more difficult and the power consumption dramatically increases [3-4]. Then, performing the FFT at the optical domain allows the speed requirements to be relaxed and the energy consumption to be reduced. The traditional optical FFT according to Marhic supplemented by optical sampling has been implemented as OOFDM demultiplexer [5]. However, this solution is difficult to implement and stabilize since each arm of the FFT structure must be stabilized with respect to each other, thereby limiting *N* to a small number for practical cases. On the other hand, other all-optical FFT methods based on a cascade of delay interferometers (DIs) have also been proposed [6] so that re-ordening of various FFT elements reduces the complexity of the architecture. In such a system, by properly tuning the phases and delays in each DI, any arbitrary FFT coefficient of the signal can be selected. Following this scheme, in this paper we propose a new OOFDM signal demultiplexing system based on integrated photonic ring resonators (RR), providing a compact and cost-effective solution. Indeed, Silicon-on-Insulator (SOI) has become an attractive technology to enable the miniaturization of integrated photonic circuits down to micrometer length scale, with submicron cross-sections for individual waveguides. Then, the miniaturization of filtering devices such as ring resonators may reduce the cost and the complexity of the OOFDM system, and SOI devices can benefit from low-cost fabrication using well-developed CMOS technologies. Moreover, the small dimension of SOI-RR devices allow the integration of many devices on the same chip, enabling high-level functionalities such as ultrafast all-optical signal processing.

Previous results have proposed the use of a ring resonator for orthogonal sub-band demultiplexing in an Orthogonal Band Multiplexing (OBM)-OOFDM system [7]. In this paper, we design a new OOFDM demultiplexer capable of OFDM subchannel extraction, which exploits the advantages of compact integrated photonic ring resonators. Compared with [7], our architecture performs a more selective filtering since it demultiplexes subchannels within an OOFDM sub-band instead of demultiplexing OOFDM sub-bands as proposed in [7]. The scheme of such a device based on SOI-RRs is shown and successful demultiplexing of four OFDM subchannel consisting of 40-Gb/s-per subchannel NRZ-OOK signals is demonstrated. Simulation results show excellent BER performance for each demultiplexed OFDM subchannel and error free operation is obtained.

II. OPERATION PRINCIPLE OF RING RESONATOR-BASED FILTERS

Ring Resonators are versatile wavelength-selective elements that can be used to synthesize a wide class of filter functions [8]. A typical structure of a RR is shown in Fig. 1. The basic configuration, which consists of unidirectional coupling between a RR with radius *R* and a waveguide, is shown in Fig. 1.a. In the former case this leads to two-port devices which act as all-pass filters.

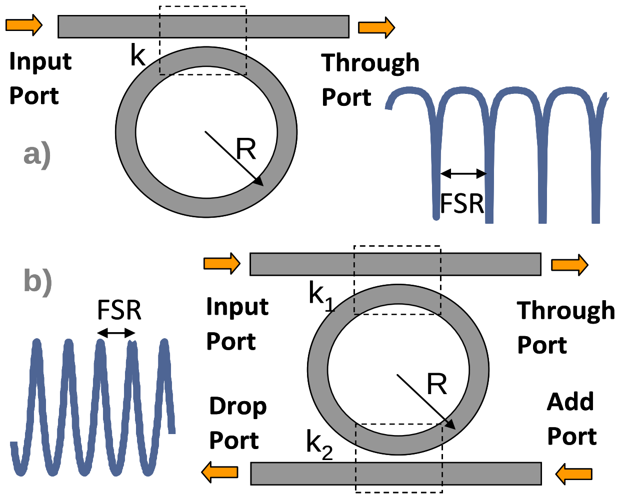

Fig. 1. Ring resonator structure: a) All-pass filter; b) Add-drop filter

Such a device exhibits a periodic cavity resonance when light travelling the ring acquires a phase shift corresponding to an integer multiple of 2π radians, which indicates that the wavelength on resonance is fully extracted by the resonator from the waveguide. This behaviour corresponds to a notch filter. On the other hand, a RR consisting of a ring plus two straight waveguides represents a 4-port structure, as illustrated in Fig. 1.b. The ring (radius R) and the port waveguides are evanescently coupled and a fraction k_1 of the incoming field is transferred to the ring. When the optical path-length of a roundtrip is a multiple of the effective wavelength, constructive interference occurs and light is 'built up' inside the ring. As a consequence, periodic fringes appear in the wavelength response at the output ports as shown in Fig. 1.b. At resonance the drop port shows maximum transmission since a fraction k_2 of the built-up field inside the ring is coupled to this port. Conversely, in the through port the ring exhibits a minimum at resonance. Then, because this configuration behaves as a narrow-band amplitude filter that can add or drop a frequency band from an incoming signal, it is commonly called an add–drop filter.

In the case of a ring coupled to one ore more bus waveguides the resonator features are determined by the coupling ratios, k, and the internal waveguide losses, α (zero loss: α=1). In particular, for the all-pass configuration, the electrical field at the through port is given by [8]:

$$E_{through} = \frac{t - \alpha e^{j\theta}}{1 - \alpha t e^{j\theta}} \quad (1)$$

where t is the transmission coefficient ($t = \sqrt{1-|k|^2}$), and $\theta = \frac{\omega L}{c} = 4\pi^2 n_{eff} \frac{R}{\lambda}$ is the phase, being L the circumference of the ring which is given by $L=2\pi R$, R being the radius of the ring, c the phase velocity of the ring mode ($c=c_0/n_{eff}$), and n_{eff} the effective refractive index.

For the add-drop configuration, the electrical fields at the through and drop ports are:

$$E_{through} = \frac{t_1 - \alpha t_2^* e^{j\theta_1}}{1 - \alpha t_1^* t_2^* e^{j\theta_1}} \quad (2)$$

$$E_{drop} = \frac{-k_1^* k_2 \alpha_{1/2} e^{j\theta_{1/2}}}{1 - \alpha_{1/2}^2 t_1^* t_2^* e^{j\theta_1}} \quad (3)$$

In this configuration, t_1, t_2, k_1, and k_2 are the transmission and coupling coefficients for the upper and lower couplers, respectively. Moreover, $\alpha_{1/2}$ and $\theta_{1/2}$ are used for half round trip loss and phase.

The difference in position between two consecutive resonant peaks (see Fig. 1) is called the Free Spectral Range (FSR) and is determined by the cavity roundtrip period. An increase of the FSR is inversely proportional to the cavity length. The FSR is given by:

$$FSR = \frac{\lambda^2}{n_g L} \quad (4)$$

being n_g the group refractive index.

Additionally, it should be noted that filter response of the ring could be tuned thermally or by applying voltage.

Once defined the key parameters of the resonator, we introduce the OOFDM demultiplexing system based on the cascade of several RRs. In particular, we show that by properly adjusting some parameters of RRs, we can demultiplex OOFDM signals in a similar way to optical FFT implementations based on DIs [6].

A. *Integrated Photonic Ring Resonators for OFDM demultiplexing*

As commented before, in OOFDM the subcarriers are spaced so tightly that their spectra overlap so that the whole of the subcarriers in an OFDM channel can no longer be demodulated by a simple filter. As a consequence, an appropriate receiver must be used for proper OOFDM demultiplexing. In this section, we propose a scheme based on RRs in which the demultiplexing of the OFDM subchannels is performed at the optical domain. The proposed scheme follows an architecture similar to that presented in [6] for optical FFT implementation.

For OFDM applications, the FFT of order N is able to discriminate N individual frequency components of the input signal. Indeed, the FFT acts as a periodic filter in the frequency domain with a FSR of $N\Delta\omega$ (where $\Delta\omega$ is the subcarrier frequency spacing). Hence, the FFT of order N ($N=2^p$, p: integer) can be implemented optically by cascading a *N/2-th* order FFT and a delay interferometer with delay T/N and a specific phase shift. Each DI is also a periodic filter with FSR equal to $N\Delta\omega/2p$ where p is the index of the FFT stage. Thus, by cascading a sufficient number of DIs with correct delay and phase, any arbitrary frequency component can be isolated. Fig. 2 shows the total intensity transfer function of the DI-based OFDM demultiplexer for N=4.

Following this idea, we propose a scheme in which each DI is replaced by a RR filter. Then, the optical circuit for N-subcarrier demultiplexing ($N=2^p$) consists of a cascade of p RRs. Each RR has a FSR of $N\Delta\omega/2p$, depending on the FFT stage. The cascade of RRs is followed by a RR-based bandpass filter (add-drop configuration) to suppress crosstalk and improve the filter performance. Fig. 3 shows the design of the OOFDM demultiplexing system based on RRs for N=4 (4 subcarriers).

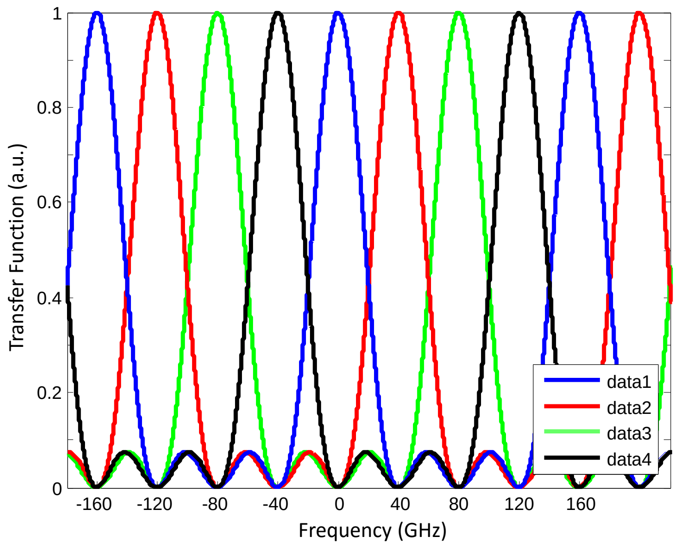

Fig. 2. Total intensity transfer function of the OFDM demultiplexer based on DIs for N=4.

The system is composed of the cascade of two ring resonators acting as a notch filter (only the output through port is used) and an additional add-drop filter. The principle operation of the OOFDM demultiplexer is as follows. The OOFDM signal is launched to the first RR (RR1) through the input port. The wavelengths on resonance are fully extracted by the resonator so that this RR acts as a notch filter. Then, by properly adjusting the FSR, at the through port the adjacent OFDM subchannels to the desired subcarrier can be filtered-out. Similar to RR1, RR2 extracts the further adjacent subchannels and finally the desired OFDM subchannel is obtained at the drop port of the RR3.

Table 1 shows the simulation parameters for the RRs used for optical demultiplexing of a 4x40Gb/s OOFDM signal. The number of subcarriers is maintained low to minimize cost and complexity and to avoid the effect of the high peak-to-average power ratio (PAPR) of the transmitted signal. The RR1 has a FSR of 80 GHz whereas the RR2 and RR3 have a FSR of 160 GHz, which leads to an overall FSR of 160 GHz. The key RR parameters to perform a successful OOFDM demultiplexing are the coupling ratios (*k*), the FSR and the ring radius, *R* (Table 1).

TABLE 1. Simulation parameters

Notch Filter – Ring Resonator 1	
R_1	132.77 µm
$k_{1\text{-}RR1}$	0.7
$k_{2\text{-}RR1}$	0.65
$FSR_{1\text{-}RR1}$	80 GHz
Notch Filter – Ring Resonator 2	
R_2	66.38 µm
$k_{1\text{-}RR2}$	0.65
$k_{2\text{-}RR2}$	0.6
$FSR_{2\text{-}RR2}$	160 GHz
Add-Drop Filter – Ring Resonator 3	
R_2	66.38 µm
$k_{1\text{-}RR3}$	0.6
$k_{2\text{-}RR3}$	0.6
$FSR_{2\text{-}RR3}$	160 GHz

In order to take into account the height of the photonic structure (typically around 220 nm) an effective refractive index of 2.8 for the silicon has been considered in the 2D simulations carried out. The group refractive index is 4.5 and the ring loss is considered to be around 10 dB/cm (which is a typical value). Moreover, it should be noted that the distance between the rings is assumed sufficiently large so that a ring is only coupled to the other rings through the waveguides and not directly. Fig. 4 shows the intensity transfer function and phase response for the OOFDM demultiplexer based on RRs. Moreover, Fig. 5 depicts the transfer function of the optical demultiplexer for each OFDM subchannels (data 1, data 2, data 3 and data 4). It should be mentioned that for higher number of subcarriers, the number of required RRs can be reduced. As first few RRs stages have the largest impact on the overall performance, the RRs placed at the last stages (RRs with largest FSRs) can be replaced by standard optical filters, simplifying the system implementation in a similar way to that proposed in [6].

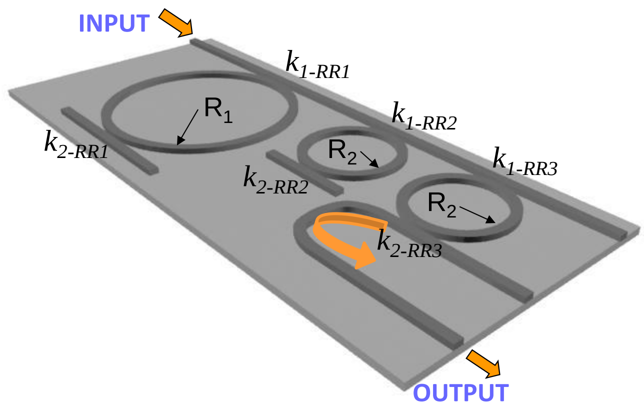

Fig. 3. Design of the OFDM demultiplexing system based on cascaded ring resonators for N=4 (4 subcarriers).

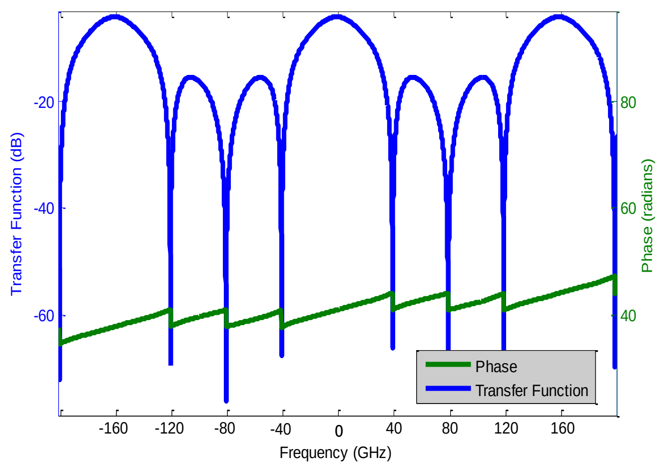

Fig. 4. Intensity transfer function and phase response of the RR-based OFDM demultiplexer for N=4.

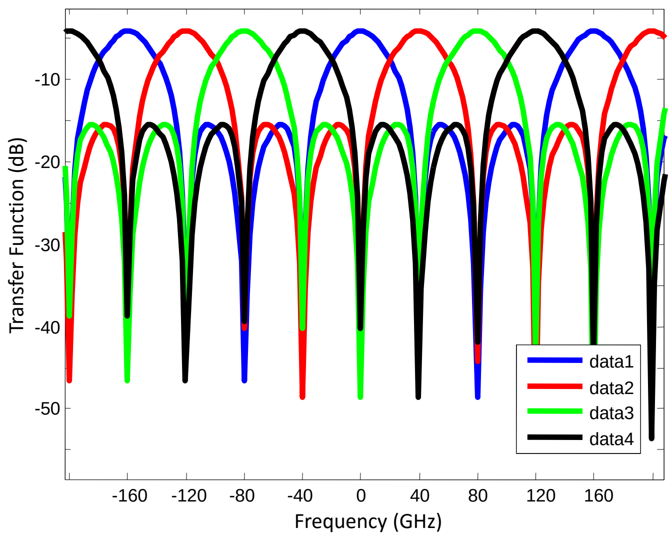

Fig. 5. Transfer function of the cascaded ring resonators for each OFDM subchannel (data1, data2, data3 and data4).

III. SIMULATION OF THE OOFDM SYSTEM USING RING RESONATORS AS OPTICAL OFDM DEMULTIPLEXERS

To verify the feasibility of the OOFDM demultiplexing operation, simulation results are carried out by using VPI Photonics Inc. software. In Fig. 6 we show the schematic of the simulation set up used for the transmission of the OOFDM signal. We generate 40-GHz spaced optical frequency comb by modulating the continuous wave (CW) laser output (1550 nm) with an RF tone using a Mach-Zehnder modulator (MZM) followed by a phase modulator, Fig. 6.a [9]. The comb is then filtered and each optical subcarrier is divided, individually modulated with an intensity modulator and finally coupled to create an OOFDM signal, Fig. 6.b. The bit rate of each subcarrier equals the optical subcarrier spacing in creating the OOFDM signal. Indeed, each subcarrier is modulated by 40-Gb/s NRZ OOK data. We filter 4 subcarriers to obtain an OOFDM signal of 160 Gb/s (4x40Gb/s). After forming the OOFDM signal, the channel spectra overlap significantly and thus can no longer be demultiplexed by standard bandpass optical filters without a high power penalty.

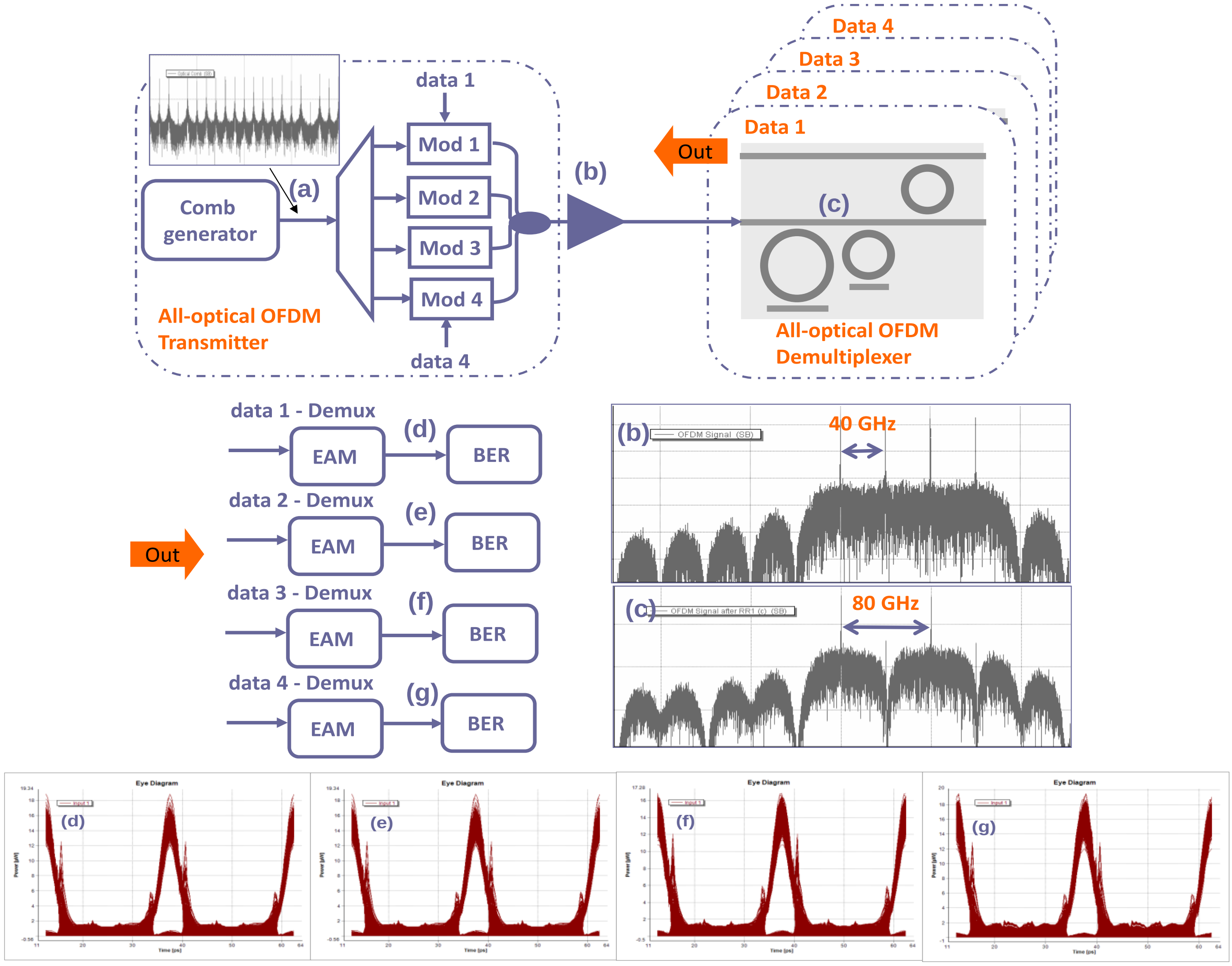

Fig. 6. Set up of OFDM system. a) Output of the comb generator; b) Four subcarriers of the comb source are filtered and modulated individually before being combined to form the 160-Gb/s OFDM signal; At the receiver, the subchannels are demultiplexed using the RR-based OFDM demultiplexer. c) Adjacent OFDM subchannels to the desired subcarrier can be filtered-out after the first RR (RR1); d-g) The resulting signals after the OFDM demultiplexer are sampled by EAM modulator and photodetected. The eye diagram of each OFDM subchannel is shown

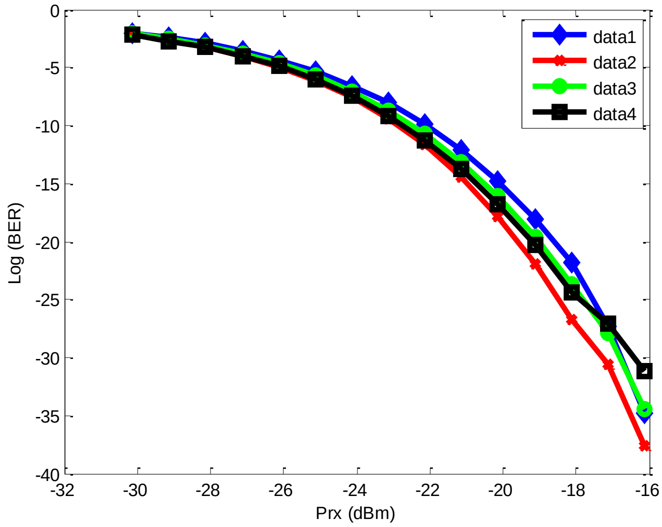

Fig. 7. BER performance of the each OFDM subchannel (data1, data2, data3, data4).

After optical amplification, the OOFDM signal is then launched into standard single mode fiber (SSMF) prior to OOFDM demultiplexing based on the cascade of RRs for subchannel selection. The optically-demultiplexed OFDM subchannels at different subcarriers are finally photodetected after optical sampling, which is performed by using electro-absorption modulators (EAMs). A clearly opened eye pattern is observed at the output of the EAM, confirming that the RR-based scheme can be used for OOFDM demultiplexing (Fig. 6.d-g).

To evaluate the performance of the all-optical RR-based OOFDM demultiplexer, we measure the bit error rate (BER) versus receiver input power for the four different subchannels. The results depicted in Fig. 7 show an excellent BER performance with error-free operation.

IV. CONCLUSION

OOFDM is shown to be an efficient modulation format for long-haul optical transmission systems. In this paper, we propose a novel all-optical OFDM demultiplexer consisting of a cascaded of ring resonators. The proposed OFDM demultiplexer can be easily achieved under current Silicon on Insulator technologies, which provides a compact and cost-effective solution. An RR-based OFDM demultiplexing system for 4x40-Gb/s OFDM is validated. Simulations show its effectiveness by demultiplexing a desired subchannel from the 160-Gb/s OFDM signal. Excellent BER performance with error-free operation for each subchannel is observed.

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