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Multi-Channel 40 Gbit/s NRZ-DPSK Demodulation Using a Single Silicon Microring Resonator

Yunhong Ding, Jing Xu, Christophe Peucheret, Minhao Pu, Liu Liu, Jorge Seoane, Haiyan Ou, Xinliang Zhang, and Dexiu Huang

Abstract—We comprehensively analyze the demodulation of wavelength division multiplexed (WDM) non return-to-zero differential phase-shift keying (NRZ-DPSK) signals by a single microring resonator. Simultaneous demodulation of multiple 40 Gbit/s WDM NRZ-DPSK channels is demonstrated using a single silicon microring resonator with free spectral range (FSR) of 100 GHz. Bit error measurements show very good performance for both through and drop port demodulations for all channels, and the drop port demodulation exhibits better wavelength detuning tolerance than for demodulation using a Mach-Zehnder delay interferometer (MZDI).

Index Terms—Demodulation, differential phase shift keying (DPSK), microring resonator, silicon photonics.

I. INTRODUCTION

DIFFERENTIAL phase-shift keying (DPSK) is a promising modulation format for optical communication networks. Compared to on-off keying (OOK) formats, DPSK exhibits a 3 dB improvement in receiver sensitivity when balanced detection is employed, and is more tolerant to fiber nonlinearities [1]. Delay interferometers (DI), in which one-bit delay between the two arms of the interferometer realizes conversion from phase modulation to intensity modulation, are typically applied to demodulate DPSK signals and have been implemented as Mach-Zehnder [2] or Michelson structures [3]. The use of delay interferometers relying on a birefringent fiber has also been reported [4], [5]. Other approaches have also been proposed and demonstrated, including the use of optical bandpass filters [6] or of a delay-asymmetric nonlinear loop mirror [7]. One important issue to be taken into account in

photonic integrated circuits is the possible polarization dependence of the demodulator, which can be reduced by appropriate techniques [8].

In wavelength division multiplexing (WDM) networks, the use of a single device to simultaneously demodulate a number of channels would offer a much preferred cost effective solution. Such an approach has been explored using frequency periodic filters, including fibre Bragg gratings arrays [9], sampled fiber gratings [10], delay interferometers [11] and arrayed waveguide grating (AWG) de-multiplexers [12].

Silicon microring resonators (MRRs) are compact and versatile devices whose use as DPSK demodulators has been recently proposed [13] and demonstrated [14] for single channel operation. This scheme is also foreseen to be very attractive for multi-channel applications due to its compact size, integration ability, and CMOS compatible fabrication process. However the optimization of MRRs for WDM demodulation of DPSK signals has not been reported so far.

In this paper, we comprehensively analyze the performance of WDM demodulation of non return-to-zero DPSK (NRZ-DPSK) signals at 40 Gbit/s based on a single MRR. Multiple channels WDM NRZ-DPSK demodulation is demonstrated at 40 Gbit/s by a single silicon MRR with free spectral range (FSR) of 100 GHz and Q value of 6700. Both the through and drop port demodulations exhibit very good and similar bit error ratio (BER) performance for all the channels. The wavelength detuning tolerance is further experimentally characterized, showing similar wavelength detuning sensitivity compared to Mach-Zehnder delay interferometers (MZDIs) for through port demodulation, and improved wavelength detuning tolerance for drop port demodulation.

II. PRINCIPLE OF OPERATION AND SIMULATIONS

A. Principle

The principle of NRZ-DPSK demodulation using a MRR is to convert phase modulation to amplitude-modulation [12] by exploiting the discriminating filter property of the MRR transfer function. The general layout of the add/drop MRR used in the present work is represented in Fig. 1.

The transfer functions of the through and drop ports of the MRR can be expressed as

$$t_{\text{through}} = \frac{r[1 - a \exp(-j\theta)]}{1 - ar^2 \exp(-j\theta)} \quad (1)$$

$$t_{\text{drop}} = -\frac{\kappa^2 \sqrt{a} \exp(-j\theta/2)}{1 - ar^2 \exp(-j\theta)} \quad (2)$$

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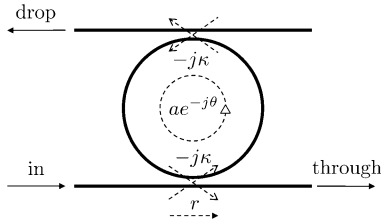


Fig. 1. General layout of an add/drop MRR.

where it is assumed that the MRR is geometrically symmetrical with identical through and drop coupling regions. r and κ are the field transmission and coupling coefficients of the coupling regions of the resonator, respectively, satisfying the relation $|r|^2 + |\kappa|^2 = 1$ for lossless coupling. θ and a are the roundtrip phase shift and field transmission coefficients along the ring waveguide, respectively. NRZ-DPSK signals can be demodulated by the MRR, resulting in the generation of alternate-mark inversion (AMI) and duobinary (DB) signals [13] at the through and drop ports, respectively. Thanks to the periodic nature of the frequency response of the MRR, simultaneous multiple WDM NRZ-DPSK demodulation can be achieved by tuning the carrier wavelength of each channel so that it coincides with one of the notches of the through transfer function. The demodulated AMI signals can then be wavelength de-multiplexed using an optical bandpass filter (OBPF) or a wavelength de-multiplexer such as an AWG. Similar multi-channel operation can also be achieved with the drop port of the MRR, resulting in the generation of DB signals.

B. Influences of Q Value of MRR and Bandwidth of OBPF

For MRR-based WDM NRZ-DPSK demodulation, the demodulation performance is influenced not only by the Q value of the MRR, but also by the bandwidth of the OBPF or AWG used for de-multiplexing. In this section, the influence of the MRR and OBPF bandwidth on the performance of NRZ-DPSK demodulation is analyzed numerically for 40 Gbit/s operation. In the following analysis, the transfer function of the de-multiplexing OBPF is modeled as a 1st order Gaussian type filter and its bandwidth is defined as full-width at half-maximum (FWHM). The Karhunen-Loève expansion method [15], [16] is applied to evaluate the BER performance for a receiver, which is assumed to be limited by amplified spontaneous emission (ASE) noise. Pre and post-detection filters modeled as 1st order Gaussian response with FWHM bandwidth of 320 GHz and 5th order Bessel response with 3-dB cut-off frequency of 30 GHz are employed in the numerical analysis. Throughout this paper, the optical signal-to-noise ratio (OSNR) is defined with a 0.1 nm bandwidth for the integration of the ASE noise spectral density. A pseudo-random binary sequence (PRBS) of length $2^7 - 1$ is adopted for all simulations. Fig. 2(a) and (b) shows the required OSNR (to obtain a BER of 10^{-9}) for the MRR demodulated AMI and DB signals under different bandwidths of the de-multiplexing OBPF and power coupling coefficients $|\kappa|^2$ (or equivalently Q values) of the MRR. One can find that, as the bandwidth of the OBPF increases, and $|\kappa|^2$ increases (or the corresponding Q value of the MRR decreases), a smaller OSNR is required to obtain a BER of 10^{-9} for the AMI signal

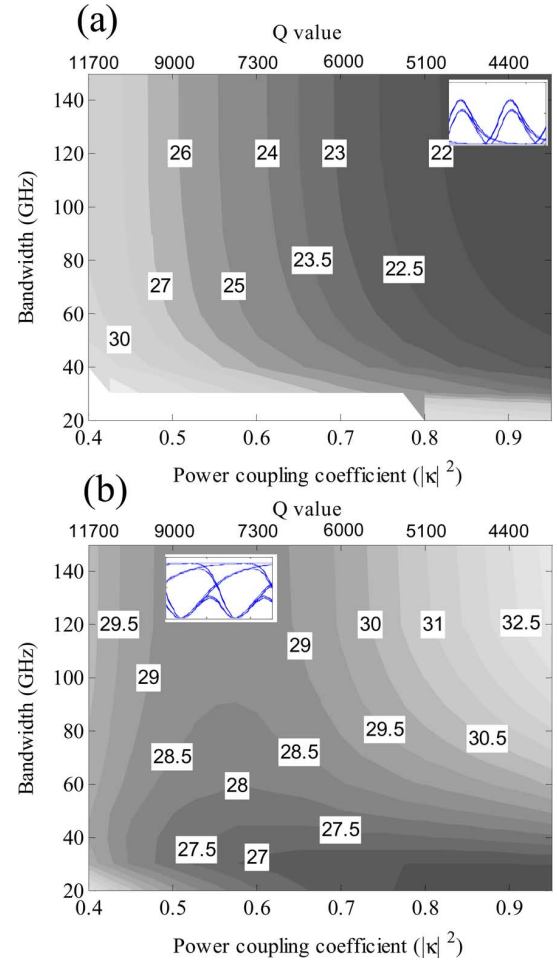


Fig. 2. Simulated required OSNR (to obtain a BER of 10^{-9}) at a BER of 40 Gbit/s versus power coupling coefficient of the MRR and 3 dB bandwidth of the de-multiplexing OBPF for (a) through and (b) drop ports of the MRR. $\alpha = 0.96$. The insets represent the simulated eye-diagram with de-multiplexing OBPF bandwidth of 65 GHz and MRR coupling coefficient $|\kappa|^2 = 0.65$.

at the through port, as shown in Fig. 2(a). In this case, the notch in the transfer function of the MRR mostly determines the phase-to-intensity conversion performance and the OBPF bandwidth has little influence, provided it is sufficiently large not to truncate the demodulated signal spectrum. However, for the demodulated DB signal at the drop port, an optimum OBPF bandwidth should be chosen depending on the $|\kappa|^2$ value in order to achieve the lowest OSNR requirement, as shown in Fig. 2(b). This is because the demodulation at the drop port essentially depends on the OBPF bandwidth, since in this case the transfer function of the MRR is nearly constant over most of the NRZ-DPSK signal bandwidth for low Q values of the MRR. The dependence of the demodulation performance at the drop port on the OBPF bandwidth is in agreement with earlier results where a single OBPF was used for demodulation and where an optimum bandwidth was also identified [6].

Fig. 3 shows a comparison of the OSNR requirement to achieve a BER of 10^{-9} as a function of the OBPF FWHM bandwidth when demodulation is performed using either a MZDI followed by an OBPF, a MRR followed by an OBPF, or only an OBPF. One can find that, as the bandwidth of the OBPF decreases, the AMI and DB signals demodulated by the MZDI

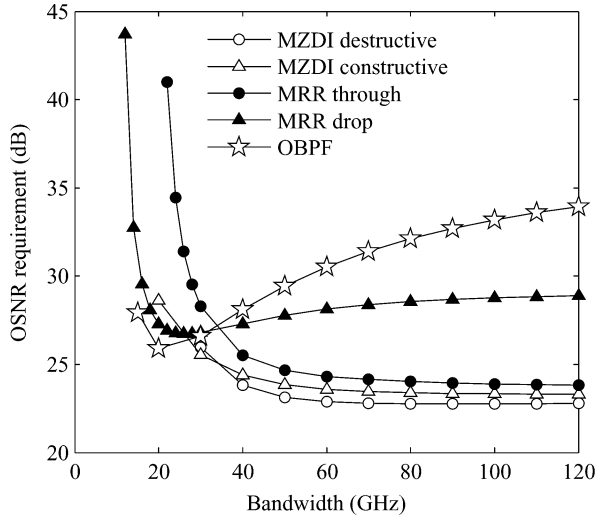


Fig. 3. Simulated required OSNR (to obtain a BER of 10^{-9}) as a function of the bandwidth of the OBPF for the demodulation of 40 Gbit/s NRZ-DPSK signals using a MZDI followed by an OBPF, a MRR followed by an OBPF as well as only an OBPF. All devices are assumed to be perfectly tuned to the NRZ-DPSK signal centre frequency. $a = 0.96$ and $|\kappa|^2 = 0.63$ for the MRR.

and the DB signal demodulated by the MRR are consistently degraded. However, an optimum bandwidth exists for the DB signal demodulated at the drop port of the MRR and the signal demodulated by an OBPF alone. This optimum bandwidth is equal to about 30 GHz for MRR demodulation, while it is found to be equal to about 0.6 times the bit rate, corresponding to 24 GHz, for OBPF demodulation, in agreement with [6]. At lower OBPF bandwidths the signal suffers from distortion and inter-symbol interference (ISI), while if the bandwidth is increased, no more phase-to-intensity conversion occurs in the case of OBPF demodulation. Even though a single OBPF with optimized bandwidth could be used for demodulation, only some categories of filters, such as Bragg gratings, are suitable for balanced detection [10]. MRR demodulation enables the simultaneous generation of two complementary signals at the drop and through ports, thus allowing balanced detection, which will be detailed further in Section II-D.

C. Wavelength Detuning Sensitivity

In real applications, some wavelength detuning may exist between the centre wavelength of the NRZ-DPSK signal and the transfer function of the MRR. Fig. 4(a) illustrates the simulated wavelength detuning sensitivity of the MRR and MZDI demodulations without OBPF. One can find that for MZDI demodulation, the OSNR requirements for the destructive (AMI) and constructive (DB) signals exhibit similar wavelength detuning dependence. For MRR demodulation, both through (AMI) and drop (DB) signals reveal better wavelength detuning sensitivity. The best wavelength detuning sensitivity can be obtained for the DB signal, but the OSNR requirement is about 6 dB higher than for the other schemes. On the other hand, the bandwidth of the de-multiplexing OBPF also plays an important role in the wavelength detuning tolerance for both MRR and MZDI demodulation. Fig. 4(b) illustrates the wavelength detuning tolerance (specified at 3 dB OSNR requirement degradation) as a

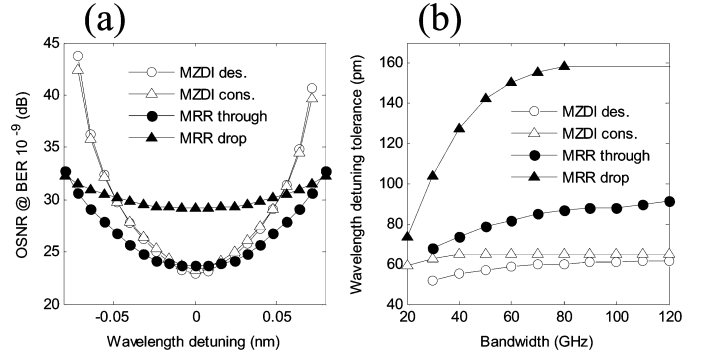


Fig. 4. (a) Simulated required OSNR (to obtain a BER of 10^{-9}) versus wavelength detuning for the 40 Gbit/s AMI and DB signals demodulated using a MRR or an MZDI. (b) Wavelength detuning tolerance (at 3 dB OSNR requirement degradation) for the MZDI and MRR demodulation for different bandwidths of the de-multiplexing OBPF. $a = 0.96$ and $|\kappa|^2 = 0.63$ are used for the MRR.

function of the OBPF bandwidth for the different demodulation schemes. One can find that the wavelength detuning tolerance of the MRR demodulation is better than that of the MZDI demodulation, especially for drop demodulation. However, as the bandwidth of the OBPF decreases, the wavelength detuning tolerance will be degraded more for MRR demodulation than for MZDI demodulation.

D. Balanced Detection

One of the well known benefits of DPSK modulation is its ~ 3 dB sensitivity advantage compared to on-off keying (OOK) when balanced detection is used [1]. It is therefore important to check if the same advantage holds in the case of MRR demodulation. Furthermore, since the performance of balanced receivers used in conjunction with MZDI demodulators is known to be dependent on the optical bandwidth [17], [18], it is important to assess the optical bandwidth tolerance of balanced receivers employing MRRs. For this purpose, the OSNR sensitivity of balanced detection is calculated as a function of the optical bandwidth for demodulation using an MRR with $|\kappa|^2 = 0.63$ and compared to the case of MZDI demodulation. In order to ensure an appropriate model is used, the BER is calculated using error counting and the sensitivity is now defined as the OSNR required to obtain a BER of 3.3×10^{-3} at the bit rate of 42.7 Gbit/s (corresponding to a BER of 10^{-12} when forward error correction with a 7% redundancy ratio is used). Error counting is aborted after a minimum of 100 errors are detected. The results are shown in Fig. 5. Since the numerical approach is different from the one used to generate the results in the previous sections, it is important to ensure both methods are consistent. The OSNR requirement is also calculated using the Karhunen-Loève expansion method at 42.7 Gbit/s for a target BER of 3.3×10^{-3} for single-ended detection at the through and drop ports of the MRR. The results are compared to those of error counting simulations in Fig. 5, showing good agreement. It can be seen that balanced detection used in conjunction with MRR demodulation presents a ~ 3 dB sensitivity advantage compared to single-ended detection at the through port for a typical optical bandwidth value of 50 GHz, while it only performs ~ 1.5 dB worse than when an MZDI is used.

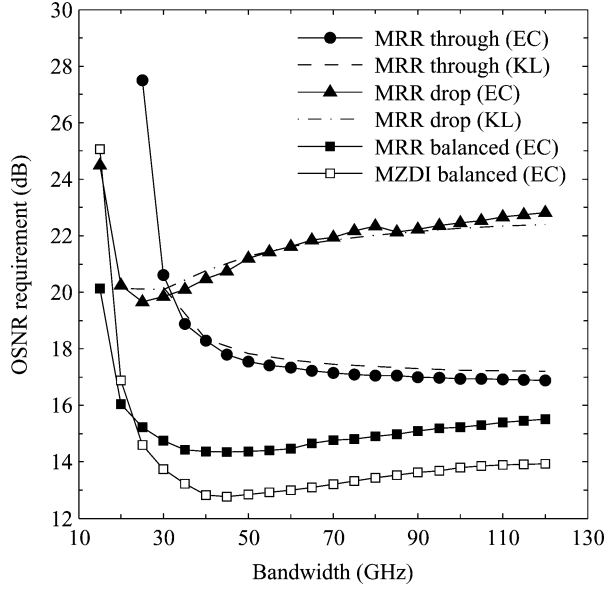


Fig. 5. OSNR requirement at a BER of 3.3×10^{-3} for a 42.7 Gbit/s NRZ-DPSK signal demodulated using an MRR with $|\kappa|^2 = 0.63$ and an MZDI. Single-ended detection at the through and drop ports, as well as balanced detection are considered for the MRR, while only balanced detection is considered for the MZDI. For MRR single-ended detection, sensitivities calculated using direct error counting (EC) and the Karhunen-Loève (KL) method are compared.

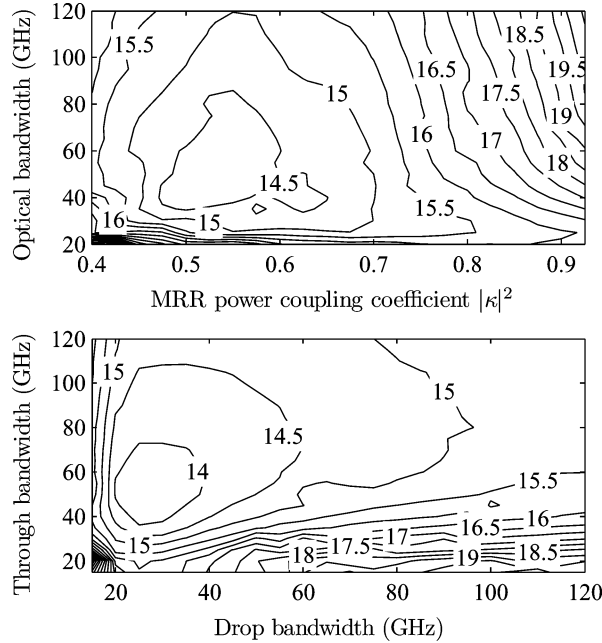


Fig. 6. Top: OSNR sensitivity at a BER of 3.3×10^{-3} as a function of MRR power coupling ratio and optical bandwidth. (Bottom) OSNR sensitivity as a function of drop and through port bandwidths for an MRR power coupling ratio of $|\kappa|^2 \sim 0.63$.

The joint optimization of the optical bandwidth and the MRR power coupling coefficient performed in Section B for single-ended detection is repeated for balanced detection. The results are shown in Fig. 6 where it can be seen that an optimum exists for a power coupling coefficient of $|\kappa|^2 \sim 0.55$ and an optical bandwidth of ~ 50 GHz, with a relatively large tolerance at this low required BER value. It should be pointed out however

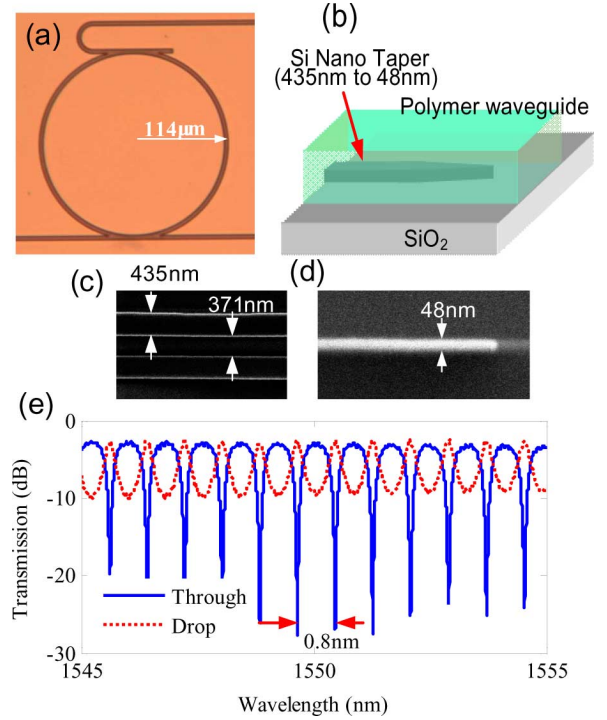


Fig. 7. (a) Optical microscope top view image of the fabricated device. (b) Design of the nano-taper coupler. (c), (d) Scanning electron microscope (SEM) pictures of the coupling region and the nano-taper. (e) Measured transmissions for the TM_0 mode of the through and drop ports of the fabricated MRR.

that, in case balanced detection is used, the receiver structure is somehow different than in the single-ended detection study, with now a DPSK modulated signal at the receiver input (where the OSNR is defined), while it used to be an OOK signal (i.e., after phase-to-intensity modulation conversion in the MRR or MZDI) in the investigation of single-ended detection. Nevertheless, since it was shown in Section B that the optimum optical bandwidths are different for drop and through demodulation, one may wonder whether an independent adjustment of the drop and through ports bandwidths may affect the demodulation performance. Those two bandwidths are consequently varied independently, and the resulting OSNR sensitivity is also represented in Fig. 6. It appears that optimum performance is indeed achieved for different optical bandwidths at the through (50 GHz) and drop (25 GHz) ports. This however only results in a marginal improvement of the receiver sensitivity, of the order of ~ 0.5 – 1 dB over a broad bandwidth range of 30–90 GHz, compared to the situation when the optical bandwidth is identical at both ports. Consequently, MRR demodulation is also shown to be a promising solution when used in conjunction with balanced detection.

III. EXPERIMENTAL DEMONSTRATION

A. Device Fabrication and Characterization

The silicon MRR was fabricated on a silicon-on-insulator (SOI) wafer with top silicon thickness of 250 nm and buried silicon dioxide of $3 \mu\text{m}$. First, diluted (1:1 in anisole) electron-beam resist ZEP520A was spin-coated on the wafer to form

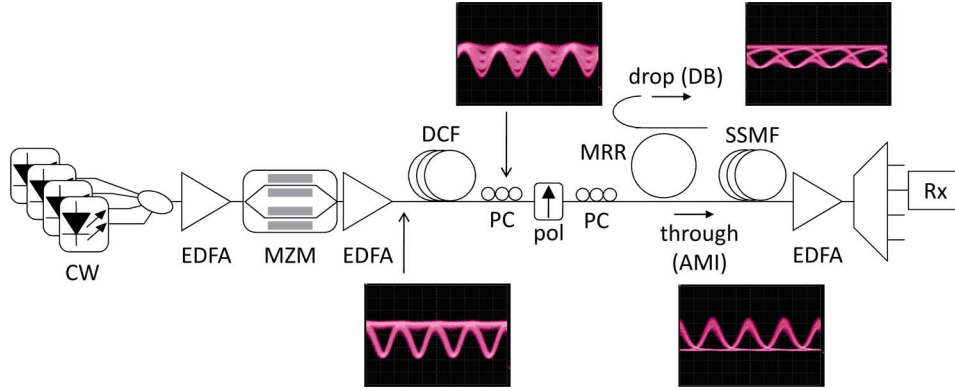


Fig. 8. Experimental setup for MRR based WDM NRZ-DPSK demodulation. The insets show the measured waveforms of the combined WDM signal at the output of the NRZ-DPSK modulator and after the de-correlation fiber, as well as the eye diagrams of a single channel at the drop and through ports of the MRR. For the filtering bandwidth dependence investigation, the AWG is replaced by an OBPF. For MZDI based demodulation the MRR is replaced by a 1-bit MZDI.

a 110 nm-thick mask layer. The structure of the device was then defined using electron-beam lithography (JEOL JBX-9300FS). After that, the sample was etched by inductively coupled plasma reactive ion etching (ICP-RIE) to transfer the patterns to the top silicon layer. A layer of 3.5 μm thick polymer (SU8-2005) was spin-coated afterwards as a top cladding layer. Top cladding regions and nano-couplers are defined by electron-beam lithography, and finally formed by developing. The radius of the MRR is 114 μm , as shown in Fig. 7(a), with a waveguide width of 435 nm and coupling gap of 371 nm for both through and drop coupling regions, as shown in Fig. 7(c). The silicon waveguide is inversely tapered to 48 nm, covered by a polymer waveguide (see Figs. 7(b) and (d)) to form a nano-coupler, resulting in ultra-low coupling loss [19] to the fiber. Fig. 7(e) shows the measured transmissions of the through and drop ports of the MRR for the TM_0 mode as a function of wavelength. The extinction ratio (ER) of the through transmission is as high as 25 dB, the measured FSR is 0.8 nm, corresponding to 100 GHz, and the Q value is 6700. The total insertion loss of the device is only 3 dB. Similarly to normal silicon nano-waveguides, the transmission of the device is polarization dependent. To reduce the polarization dependence, a polarization diversity structure can be introduced [20], [21].

B. Experimental Set-Up

The experimental setup for WDM NRZ-DPSK demodulation is illustrated in Fig. 8. Four channels of continuous wave (CW) laser light with wavelengths of 1548.65 nm, 1550.26 nm, 1551.90 nm, and 1553.54 nm (channel spacing of ~ 200 GHz) are combined in a coupler, amplified by an erbium-doped fiber amplifier (EDFA), then simultaneously modulated in the NRZ-DPSK format in a Mach-Zehnder modulator. The bit rate is 40 Gbit/s and the bit pattern length is $2^{31} - 1$. The WDM NRZ-DPSK channels are then amplified by another EDFA and de-correlated in 150 m dispersion-compensating fiber (DCF) with total dispersion of -17.4 ps/nm at 1550 nm. In order to ensure that all WDM channels are optimally coupled to the MRR, a polarization controller (PC) followed by a polarizer is first used to align all channels to the same polarization state. A second PC is then used to align the input polarization to the TM mode of the waveguide. Demodulated AMI and DB signals will be obtained

at the through and drop ports of the MRR, respectively. Afterwards, 1 km standard single mode fiber (SMF) is used to compensate the dispersion introduced by the DCF. The WDM demodulated signal is amplified by another EDFA, de-multiplexed by an OBPF or an AWG and finally detected in an optically preamplified receiver. In the experiments, the receiver power sensitivity at a BER of 10^{-9} is adopted as a performance metric.

C. Filtering Bandwidth Dependence

The influence of the bandwidth of the OBPF is experimentally analyzed for single channel operation, in which only channel 2 is switched on, as shown in Fig. 9. Fig. 9(a) shows the measured BERs of the demodulated AMI and DB signals at the through and drop ports of the MRR for different bandwidths of the OBPF. Reference curves where no OBPF is used are also shown. Fig. 9(b) represents the corresponding receiver sensitivities at a BER of 10^{-9} . One can find that, as the bandwidth of the OBPF decreases, the receiver sensitivity of the AMI signal demodulated at the through port degrades. However, an improved receiver sensitivity of the DB signal demodulated at the drop port is obtained as the bandwidth decreases over the investigated range. This is in qualitative agreement with the simulation results of Fig. 3. The measured curves however quantitatively differ from the simulated ones due to the presence of OBPFs with different transfer functions in the experimental implementation. Furthermore, the performance is also affected by the frequency response of the OBPFs employed in order to suppress out-of-band ASE noise in the preamplified receiver.

D. Wavelength Detuning Tolerance

Wavelength detuning tolerances for both through and drop port demodulations are also experimentally characterized, as illustrated in Fig. 10. The receiver sensitivity is evaluated at a BER of 10^{-9} for single channel operation without AWG. For the demodulation with a commercial fiber MZDI having a 42.7 GHz FSR, the receiver sensitivities for both constructive and destructive ports exhibit similar dependences to the wavelength detuning, with allowed detuning ranges for 3 dB power penalty of about 0.04 and 0.05 nm for the demodulated AMI and DB signals, respectively. A similar wavelength detuning sensitivity is obtained for MRR through port demodulation, with a detuning

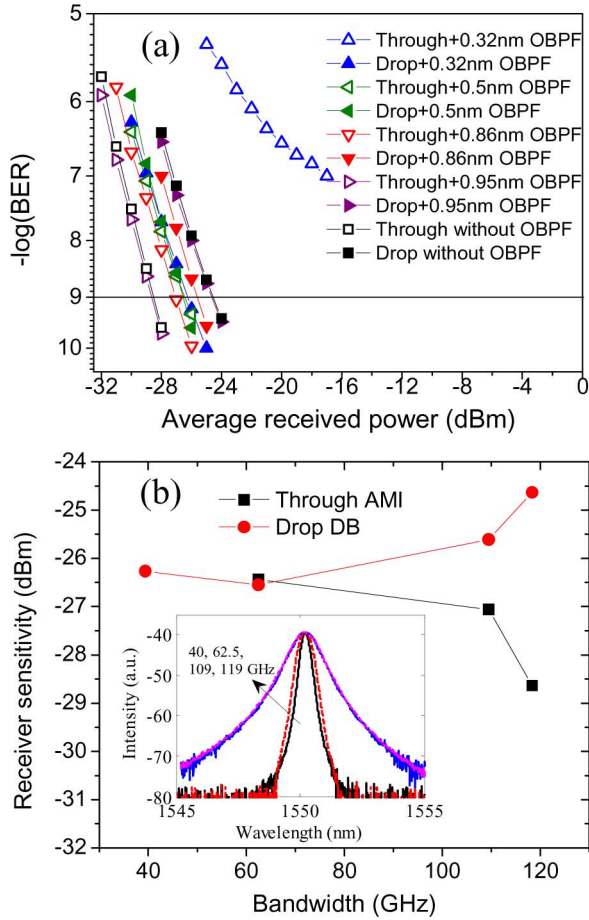


Fig. 9. (a) BER measurements of the demodulated AMI and DB signals for different bandwidths of the OBPF, as well as in the reference case when no OBPF is used. (b) corresponding power penalties at a BER of 10^{-9} compared to the case without OBPF.

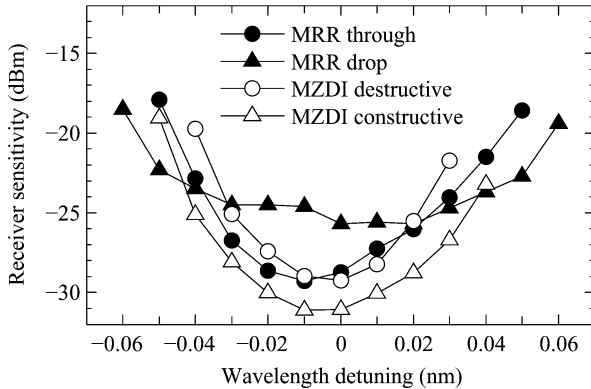


Fig. 10. Measured receiver sensitivity versus wavelength detuning for the AMI and DB signals demodulated by MRR or MZDI.

tolerance of about 0.05 nm. The best wavelength detuning sensitivity is obtained for drop port demodulation, with a wavelength detuning tolerance of 0.09 nm (all at 3 dB receiver sensitivity degradation). Those results are also in qualitative agreement with the simulations. The narrower wavelength detuning tolerance compared to the one predicted in the simulations is attributed to the impact of the ASE suppressing OBPFs in the preamplified receiver.

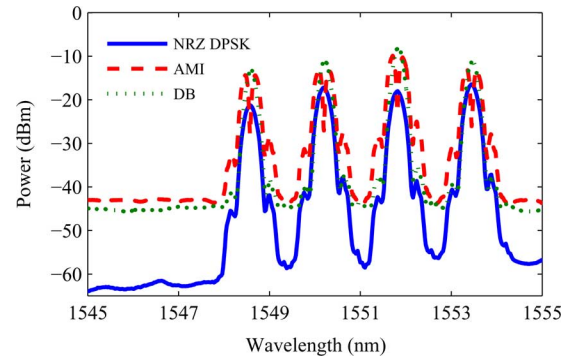


Fig. 11. Measured spectra of the WDM NRZ-DPSK signals, as well as of the WDM AMI and DB signals demodulated in a single MRR.

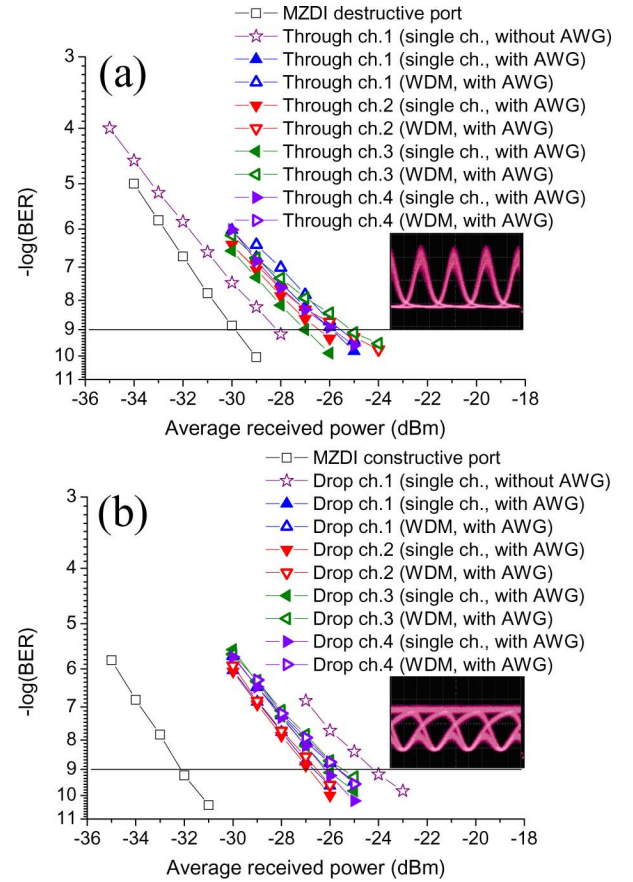


Fig. 12. BER measurements for the multiple channel (a) AMI and (b) DB signals demodulated by the MRR, as well as a single channel AMI and DB signal demodulated by the MZDI. The insets show typical eye diagrams for the AMI and DB signals demodulated by the MRR.

E. WDM Operation

Fig. 11 shows the measured spectra of the WDM NRZ-DPSK signals, as well as of the WDM AMI and DB signals demodulated in a single MRR. The notches of the through transfer function and the peaks of the drop transfer function of the MRR are aligned to the carrier wavelengths of all the WDM channels, resulting in simultaneous demodulation of all channels to the AMI and DB formats, respectively. Fig. 12(a) and (b) presents BER measurements for all channels at the output of the through (AMI) and drop (DB) ports. The inset pictures illustrate very

clear eye-diagrams for the demodulated AMI and DB signals. For comparison purpose, the MRR is also substituted with a commercial fiber MZDI with 42.7 GHz FSR used for single channel demodulation. Although the BER for both through and drop port demodulations are worse than that of the MZDI, all the four channels reach bit error rates below 10^{-9} , without noticeable error floor. For through port demodulation, the AWG induces about 1–2 dB power penalty, and about 0.5–1 dB power penalty is further caused by the crosstalk between channels. However, for drop port demodulation, the AWG improves the receiver sensitivity by about 3 dB, and around 0.5 dB power penalty is further introduced by the crosstalk. As there is a trade off between the performance of the demodulated AMI and DB signals [13], it is found that the MRR with Q value of 6700 associated with the AWG, lead to similar receiver sensitivities for both through and drop port demodulations.

IV. CONCLUSION

We have comprehensively analyzed the performance of WDM NRZ-DPSK demodulation at 40 Gbit/s based on a single MRR. A detailed comparison between the MRR, MZI and OBPf demodulations has been made, which shows the advantages of MRR based WDM NRZ-DPSK demodulation. The scheme has also been shown to be promising in case balanced detection is used. Multiple channels WDM NRZ-DPSK demodulation at 40 Gbit/s has been demonstrated by a single silicon MRR with FSR of 100 GHz and Q value of 6700. Both the through and drop port demodulations exhibit very good and similar BER performance for all the channels. Better wavelength detuning sensitivity is obtained for drop port demodulation compared to the MZDI demodulation.

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