ABSTRACT To cope with the exponential increase in internet services and corresponding data traffic, especially data centers and access networks require new high data rate transmission methods with low cost, very small package and low energy consumption. In this paper, we demonstrate a filterless, agnostic Nyquist wavelength division multiplexing (ANy-WDM) transmission system based on cascaded ring modulators and a comb source. The single ring modulator acts as a filter, filtering one of the \( n \) WDM lines, generated by the comb. The same ring modulator modulates \( k \) time division multiplexed (TDM) channels on the single wavelength. Since each WDM channel, consisting of \( k \) time domain channels, has a rectangular bandwidth, the aggregated symbol rate of the superchannel modulated by this system corresponds to the optical bandwidth of all \( n \) WDM channels together. The approach is very simple and compact. Since no optical filters, delay lines or other special photonics or high bandwidth electronics is needed, an integration into any photonics platform is straightforward. Thus, the proposed method might enable very compact, ultra-high data rate transmission devices for future data centers and access networks.

INDEX TERMS Integrated photonics, Nyquist transmission, ring modulators, WDM.

I. INTRODUCTION

According to the Cisco Annual Internet Report, the total number of internet users in 2023 will be 5.3 billion, and the number of machine-to-machine connections will increase to 14.2 billion. Additionally, 77% of the internet connections will rely on mobile devices [1]. To satisfy these data demands, the capacity of intra- and inner-data center communications as well as access networks has to be maximized [2]. Data rates of up to 1.6 Tbit/s will become essential in data centers in the near future, for instance [3] and even the peak data rates in 6G and beyond wireless cells will increase to 1 Tbit/s [4]. However besides high data rates, low cost is required especially in data centers and access networks. Therefore, an integration of the transceivers on a low cost photonic platform is needed.

Today, the systems mainly rely on high-bandwidth photonic and electronic devices. For increasing data rates, the bandwidth of these devices and their electrical energy consumption will increase [5], which makes an integration on a low cost platform challenging. An alternative might be optical superchannels [6]. These superchannels can be realized by orthogonal frequency division multiplexing (OFDM) [7] or Nyquist wavelength division multiplexing (Nyquist-WDM) [6]. However, these methods still require complex electronic-photonic signal processing, high bandwidth photonics, optical delay lines, optical filters and so on [8], [9], [10].

Recently, it has been shown, that integrated comb sources can lead to a cost effective, high data rate transmission with reduced energy requirements [11]. For the high data rate modulation of superchannels with any kind of signals by very simple electronic and photonic devices, the agnostic sampling transceiver was presented [12]. In this concept,
an optical superchannel is achieved by the combination of $n$ WDM channels, generated by a comb source, each of which modulated with $k$ TDM Nyquist channels. The transmitter and receiver for these superchannels basically consists of a modulator. For transmitting higher order modulation formats, an IQ-modulator is required in the transmitter and for demultiplexing a single Mach-Zehnder modulator (MZM) is sufficient. The MZM that can be used at the transmitter or receiver, may be with single drive [12] or dual drive ports [13]. Within this concept, analog and/or digital signals with different bandwidths and data rates can be transmitted, multiplexed, and processed into a superchannel with no need for high bandwidth electronics and photonics. Even Nyquist channels within a rectangular bandwidth can be generated and processed. Hence, the signal transmission is agnostic and can achieve the maximum possible symbol rate in the bandwidth of the superchannel [12].

Like Nyquist-WDM and OFDM the agnostic transceiver method [12] enables the transmission of the maximum possible symbol rate in the Nyquist bandwidth. However, compared to OFDM no broadband transmitters and receivers and no complex signal processing is necessary [7] and compared to Nyquist-WDM, no sophisticated broadband analog to digital conversion [9] or special source [14] and optical filter is needed.

However, the modulation of the $n$ WDM channels in the transmitter requires to use WDM filters [15], [16] or arrayed waveguide gratings (AWGs) [17] to select between the wavelengths. Thus, $n$ optical branches are established. In each optical branch, a single MZM modulator can be used for the $k$ TDM channels. Therefore, the aggregated data rate from the whole system depends on $n$ parallel optical branches. This makes the system complex. Additionally, MZMs require a quite high chip space and power consumption. The integrated MZM that has been used for the agnostic sampling transceiver in [18], had a length of 3.2 mm for each arm and a power consumption of $>1$ pJ/bit, for instance. Thus, for $n$ WDM superchannels the transmitter would require a high chip space and power just for the MZMs.

Since the radius of a ring modulator is only a few micrometers and consumes much lower power in the femtosecond range, integrated ring modulators might be a much better solution for compact devices [19]. Cascaded silicon ring modulators have successfully been used for the modulation of WDM channels, generated by a frequency comb [20], [21], [22]. Each ring modulator works as a modulator and filter for a single WDM channel. Thus, integrated WDM filters/AWGs and DMUXs are not needed.

Here, we demonstrate, how this concept can be extended for the generation of Nyquist superchannels with $n$ WDM channels without any guard band, each of the ring modulators consisting of $k$ TDM channels, which we have called filterless agnostic Nyquist-WDM (ANy-WDM). The system does not require any filter, optical delay line, special electronics or photonics. Therefore, it can easily be integrated into any photonics platform. Additionally, because of the small radius, low power consumption, and high bandwidth of integrated ring modulators, the transmitters can be very compact, making them especially attractive for data center and access network applications.

II. CONCEPT OF THE ANy-WDM SYSTEM

To show the principle of operation of the proposed filterless ANy-WDM system based on the cascaded optical ring modulators, the conventional ANy-WDM system based on multiplexers and demultiplexer is described first.

A. CONVENTIONAL ANy-WDM SYSTEM

The idea of a conventional ANy-WDM transmission system [12] is shown in Fig. 1. It is based on a WDM filter or...
AWG to select between the \( n \) wavelength lines for \( n \) optical branches. In each branch, a single MZM is used for the modulation of \( k \) TDM channels [12]. These \( k \) TDM channels can be processed in the electrical domain and modulated with one single modulator. The multiplexing of the \( k \) TDM channels is based on the orthogonality of \( k \) sinc-pulse sequences, each of which time shifted to the zero crossing of the previous one. In the equivalent frequency domain, the single sinc pulse sequence corresponds to a frequency comb with \( k \) lines, the frequency separation \( \Delta f \) and the bandwidth \( B = k \times \Delta f \). Thus, the sequences are time shifted by \( 1/B \) and the aggregated symbol rate of all \( k \) channels together corresponds to \( B \). The frequency comb can be generated by \( l = (k - 1)/2 \) sinusoidal electrical frequencies [23], [24]. All these electrical frequencies are multiplied with the data of the single channel in the electrical domain. The next channel has a time shift of \( 1/B \) to the previous one. This corresponds to a phase shift of the electrical frequencies of \( \Delta \phi = 2\pi/k \).

Therefore, the sinusoidal frequencies of the next channel can be phase shifted by \( \Delta \phi \) and modulated with the data. All the \( k \) channels are summed up and used to drive the single modulator [12]. This is done in each single branch and all \( n \) WDM channels are multiplexed together in a wavelength division multiplexer (MUX) or AWG to build the \( k \times n \) superchannel, before transmission. Since all channels can be multiplexed in the wavelength domain without any guard band, the maximum possible aggregated symbol rate in the superchannel corresponds to the bandwidth \( n \times B \).

In Fig. 1 the receiver for the detection of all \( k \) TDM channels at a single wavelength is shown. For the detection of a single channel \( C_{p,q} \), one of the branches would be sufficient. In each of the branches a Mach-Zehnder modulator driven with a number of \( l = (k-1)/2 \) sinusoidal radio frequencies with the phase shift \( (p-1) \times \Delta \phi \) is used to select the \( p \)-th (\( p = 1, 2, \ldots, k \)) TDM channel. A single intensity modulator is sufficient also for the demultiplexing of higher order modulation formats [25]. The modulator multiplies the incoming superchannel with a sinc-pulse sequence with a time shift defined by the phase shift of the radio frequencies [12]. However, this will demultiplex all TDM channels with the same time shift in all \( n \) WDM channels. To select the single TDM channel at a single wavelength \( q (q = 1, 2, \ldots, n) \) from the \( n \times k \) WDM-TDM superchannel, a local oscillator (LO) and a low bandwidth coherent detector is required. The low bandwidth of the coherent detector filters out all other mixing products of the LO signal with the superchannel. The same can be achieved with an electronic filtering after detection. This local oscillator signal can be generated by a single LO with the correct wavelength, or by one line extracted from a second integrated comb source. The required bandwidth of the LO is only \( B/2 \) and that of the coherent detector \( B/(2k) \) [26]. Please note that the bandwidth of the transmitted superchannel is \( n \times B \). Thus, for the transmitter and especially receiver, low bandwidth equipment can be used to process very high bandwidth superchannels, leading to a reduction of the SNR requirements, power consumption and costs [27].

### B. Proposed Filterless ANy-WDM System

The basic concept of our method is demonstrated in Fig. 2 and enables a drastic reduction of the hardware requirements in the transmitter. It is based on a comb source and cascaded ring modulators without any WDM filters/AWGs, delay lines or MUXs. Only one single optical branch with serial ring modulators is needed to achieve the optical superchannel. The receiver, however, is the same as that for the conventional system, saving all the advantages especially for data center and access applications.

The comb source, preferably an integrated one, generates \( n \) lines, which define the number of WDM channels. This comb source can be based on an integrated ring resonator, for instance, which enables a very precise frequency locking between the different center frequencies of the channels [28]. A phase-locking, however, is not required. For higher bandwidths modulators and a lower number of channels, the resonator based comb source might even be replaceable with dual-drive modulator [13]. A frequency jitter between the comb lines up to several percent of the channel bandwidth is tolerable and these lines do not have to be phase-locked [12]. The following single ring modulator works as a filter, by selecting one of the \( n \) WDM lines and
as a modulator, by modulating $k$ orthogonal TDM channels on the WDM line. For the wavelength selection, the resonance wavelength of each ring modulator is adjusted with a heater, or with a bias to the modulator to the specific wavelength of the comb lines. To stabilize the temperature for all ring modulators, a temperature compensation system can be employed [29]. Alternatively, a heater can be integrated with each ring [20]. However, this increases complexity and power consumption. The heat cross-talk can be effectively suppressed in densely packed photonic chips by applying an air-filled trench between the ring modulators [30].

For the multiplexing of the $k$ orthogonal TDM channels only, electrical phase shifters and mixers are required [12] and each ring modulator modulates these channels to the corresponding wavelength. Please note that the single TDM channel can be an analog or a digital one, it can be a Nyquist or a normal data channel and it can have any modulation format so the transmission is completely agnostic [12]. Each subsequent ring modulator is adjusted to the next adjacent wavelength, and will modulate the next WDM channel, consisting of $k$ TDM sub-channels. The number of TDM and WDM channels, their bandwidth and shaping can be chosen freely. However, to transmit with the maximum possible symbol rate in a given bandwidth, the single TDM channels should be Nyquist shaped with a rectangular bandwidth, which corresponds to the frequency spacing between the lines of the comb, as shown in Fig. 2.

Compared to MZM, ring modulators can have a very small radius [19]. Since no special photonic components and only low bandwidth equipment is needed, the transmitter can be very compact and easily be integrated into any photonic platform to generate and receive Tbit/s data signals.

III. SIMULATION SETUP

For the proof of concept, the simulation setup in Fig. 3 was defined using the Lumerical software package. Due to limitations of the software, the simulations were restricted to a back to back configuration. However, in experiments with MZM, integrated on a silicon-on-insulator platform, we have shown the transmission of 48 Gbit/s superchannels over 30 km of fiber without any pre- or post-compensation. For long fibers the dispersion may lead to problems for the transmission of the signal. However, since the coherent detector receives the amplitude and phase of the signal, this can be compensated by an electronic post- or pre-compensation. For the transmitter part, a comb laser source with 10 dBm power and 1 MHz linewidth is utilized to generate $n = 5$ lines with frequency spacing $\Delta f = 84$ GHz as shown in Fig. 4(a). The central frequency of the comb is adjusted to be at 193.516 THz (in the C-Band of optical communications). The selected wavelength is modulated with $k = 3$ orthogonal TDM channels with a binary phase shift keying (BPSK) in a rectangular bandwidth, resulting in a superchannel with 15 TDM-WDM channels. In the electrical domain the TDM channels are modulated to one single RF frequency of 28 GHz, phase shifted by $0^\circ$, $120^\circ$, and $240^\circ$ for the three orthogonal channels. Each phase shifted version of the RF is multiplied with a 28 GBd BPSK signal bandlimited to 14 GHz. All the three channels are added together in the electrical domain before driving the single ring modulator. Thus, the aggregated data rate of the proposed system is based on a PN ring modulator with a 10 $\mu$m radius working under reverse bias configuration. The PN ring modulator in carrier depletion mode was used because it offers a better modulation depth with higher bandwidth [19].

From the simulated intensity transfer function in Fig. 4(b) it can be seen that the modulation depth increases with reverse voltage. A modulation depth of $-34.8$ dB at $-2$ V DC voltage is obtained. The resonance point of each of the ring modulators is adjusted to match with the selected wavelength of the comb lines as can be seen in Fig. 4(c). Please note that we have assumed that the temperature of the cascaded VOLUME 10, 2022
ring modulators was stabilized during all simulations. The 3 dB electrical bandwidth of the ring modulator is 42 GHz at −2 V DC bias as presented in Fig. 4(d).

The center wavelength of the next ring modulator is adjusted to meet that of the next comb line and again modulated with three distinct TDM channels with an aggregated data rate of 84 GBd.

To demultiplex the single TDM channel from the 15 WDM-TDM superchannel, a Mach-Zehnder modulator driven with a sinusoidal frequency of 28 GHz and a phase shift of 0°, 120° or 240° selects the single TDM channel. The WDM channel is defined by the wavelength of the local oscillator (LO) and the phase shift of the sinusoidal wave defines the TDM channel. A coherent detector with a baseband bandwidth of 14 GHz demodulates the channel (amplitude and phase). In the simulation the noise of the photodiodes was 1e-22 A/Hz. The gain and noise figure of the electrical amplifier is 33 dB and 3 dB, respectively.

IV. RESULTS AND DISCUSSIONS

In this section, simulation results of the proposed system for the fifth wavelength (ring modulator # 5, please see Fig. 3) are presented. The other wavelengths show similar results. For the simulation, the 15 channels in the superchannel were demultiplexed simultaneously by using a 1:15 power splitter in the receiver.

Figure 5 depicts the rectangular spectrum shape of the multiplexed superchannel for \( n = 5 \) wavelength channels, each of which modulated with \( k = 3 \) TDM channels with total optical power of −21 dBm, without any amplification. As can be seen, there is no guard spacing between the comb lines and each single TDM channel has an almost rectangular bandwidth that corresponds to the comb spacing. The carrier at each wavelength has a higher amplitude, because the ring modulator is working at a negative bias. This bias adds an additional DC offset to the transmitted data signal of the three TDM channels and is still there after the optical modulation with the ring modulator. To suppress the carrier, the ring modulator should work at 0 V DC bias. However, because of software inefficiencies, this was not possible in the simulation. That a 0 V bias is indeed possible has been shown by experiments [31], [32]. For the demultiplexing of the WDM channel, the wavelength of the LO is adjusted to that wavelength and for the demultiplexing of the time domain channel, the sinusoidal frequency of the receiver has a phase shift of 240° (please see Fig. 3).

The comparison between the transmitted 28 GBd Nyquist BPSK signals (black) and the received data (red) of the three
FIGURE 6. Simulation results. The transmitted and received 28 Gbd bandlimited BPSK signals for the three TDM channels (applied to the fifth ring modulator) can be seen in (a), (b), and (c). The resulting eye diagrams at the receiver for these signals are shown in (d), (e), and (f).

TDM channels \( p = 1, 2, 3 \) is shown in Fig. 6(a), (b), and (c). The reception of all transmitted signals at the receiver side is demonstrated without any kind of pre- or post-compensation. Experimental transmission results with BER vs. SNR curves for agnostic signals can be found in [12]. The out-of-band noise contributions from the coherent detector and the electrical amplifier are cancelled by the rectangular electrical filter. As shown, the received signals are close to the transmitted ones. Clear eye diagrams with BERs of around \( 10^{-5}, 10^{-6} \), and \( 10^{-6} \) are achieved as shown in Fig. 6(d), (e), and (f) respectively. The measured BERs can be calculated by using (1) depending on the Q factor and the error function (erfc). The Q-factor can be measured based on the signal to noise ratio (SNR), the electrical bandwidth of the receiver \( B_c \) and the optical bandwidth \( B_o \) [33].

\[
\text{BER} = \frac{1}{2} \text{erfc}\left(\frac{Q}{\sqrt{2}}\right)
\]

(1)

where:

\[
Q = \text{SNR} + \log\left(\frac{B_c}{B_o}\right)
\]

(2)

In Tab.1, the simulation results for the log(BER) for all 15 channels are presented. All values of the BER for all channels meet the acceptable BER of \( 10^{-3} \) [34], [35].

The overall aggregated data rate of the proposed system is 420 Gbit/s for the BPSK data signals and with PAM-4 it will be 840 Gbit/s. Although the modulation of PAM-4 signals with ring modulators was demonstrated in many references such as [36] and [37], the simulation software was limited to BPSK. Recently, ring modulators with 110 GHz bandwidth have been demonstrated [37], suggesting 2.2 Tbit/s superchannels for PAM-4 modulation with three TDM, and five WDM channels.

| Central Frequency | Ch.1 | Ch.2 | Ch.3 |
|-------------------|------|------|------|
| 193.348 THz       | -5.14| -5.62| -4.72|
| 193.432 THz       | -4.75| -4.96| -4.66|
| 193.516 THz       | -4.56| -4.87| -5.12|
| 193.600 THz       | -5.21| -5.24| -5.43|
| 193.684 THz       | -4.94| -6.53| -6.22|

V. CONCLUSION

In conclusion, a compact filterless ANy-WDM transmission system was presented. It is based on a comb source and cascaded ring modulators for an agnostic Nyquist transmission. The multiplexing and demultiplexing of a WDM-TDM superchannel with 5 wavelength domain and 3-time domain channels has been shown. The aggregated data rate of this 15 BPSK superchannel was 420 Gbit/s. The system is very compact, it does not need any WDM filters, delay lines, or complicated or high-bandwidth photonics or electronics. Thus, integration into any photonics platform is straightforward. We believe that the system would be especially advantageous for data center and access network applications.

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