

All-optical OFDM demultiplexing by spectral magnification and band-pass filtering

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Abstract: We propose a simple OFDM receiver allowing for the use of standard WDM receivers to receive spectrally advanced OFDM signals. We propose to spectrally magnify the optical-OFDM super-channels using a spectral telescope consisting of two time-lenses, which enables reduced inter-carrier-interference in subcarrier detection by simple band-pass filtering. A demonstration on an emulated 100 Gbit/s DPSK optical-OFDM channel shows improved sensitivities after 4-times spectral magnification.

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1. Introduction

Optical orthogonal frequency division multiplexing (OFDM) is an attractive format for transmitting data with very high spectral efficiency and high dispersion tolerance [1–6]. In all-optical OFDM (AO-OFDM), the subcarrier multiplexing and demultiplexing is performed in the optical domain, allowing the generation of OFDM super-channels with Tbit/s capacity [7,8]. Demultiplexing of the subcarriers can be achieved by discrete optical Fast-Fourier Transformation (O-FFT) (or optical discrete Fourier transformation (O-DFT)). The DFT may be performed by passive filtering, using delay-interferometers, as suggested by M. Marhic [9]. However, the DFT requires phase-stabilisation of the optical paths in the delay-interferometers and each subcarrier subsequently requires a sampling gate to avoid detrimental inter-carrier-interference (ICI). Hence, the complexity and power consumption of the O-DFT based OFDM demultiplexer will increase with the number of subcarriers. This is in stark contrast to the well known standard DWDM receivers, mainly consisting of passive filters. The scope of this paper is to enable the reception of spectrally advanced OFDM data signals using simple standard WDM receivers by first converting the OFDM signal into a WDM-like signal compatible with a WDM receiver, see Fig. 1. In [10], it was suggested to use time lenses to perform Fourier transformations to both generate and receive an AO-OFDM signal. This proposal was based on time lenses consisting of dispersive elements and an electro-optical phase modulator acting on a frame of OFDM data, i.e. operating on a finite extent OFDM data signal limited by the finite time aperture of the phase modulation. As described in [11], it is difficult to get a strong phase modulation using electro-optic phase modulators, and in particular with a time aperture stretching over several ns, and furthermore, the dispersive elements involved before the phase modulation stage, may broaden the data pulses beyond the time aperture required. Thus, the reliability of this AO-OFDM generation and detection scheme (D-K-D) has not yet been experimentally verified.

In this paper, we propose and experimentally demonstrate all-optical OFDM demultiplexing based on spectral magnification in a spectral telescope arrangement consisting of two time-lenses and subsequently followed by a narrow optical band-pass filtering (BPF) of each sub-carrier. The spectral magnification leads to significantly reduced ICI after the BPF, thus allowing for direct detection of all subcarriers, without the need for sampling gates. Hence, full demultiplexing of an OFDM super-channel can be achieved using a single active unit. To demonstrate the principle, we use four-wave mixing (FWM) based time-lenses and demonstrate 4x spectral magnification of an emulated 100 Gbit/s DPSK OFDM super-channel with 10 subcarriers. Error-free performance and improved subcarrier sensitivities are obtained after magnification.

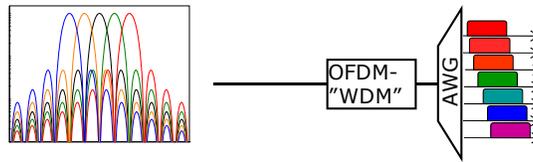


Fig. 1. Motivation: Replace optical DFT and active gates for each subcarrier with a single OFDM-to-DWDM-like converter followed by a standard passive WDM receiver, e.g. an arrayed waveguide grating (AWG).

2. Principle of spectral magnification for OFDM reception

Time-lenses are based on parabolic phase modulation and dispersion, and can be used to perform frequency-to-time [12] and time-to-frequency [13] conversion of an optical waveform. A combination of time-lenses can be employed for spectral magnification [14] or compression [15]. The magnification principle is sketched in Fig. 2 for an input OFDM waveform. Time-lens 1 converts the OFDM spectrum to the time-domain, and time-lens 2 converts back to the spectral domain. The magnification factor is determined by the ratio of the two employed parabolic chirp rates [14]. The magnified spectrum results in reduced ICI when using BPFs to extract the subcarriers as sketched in Fig. 2. Since the spectral magnification process is carried out in a coherent manner, the signal will be transform limited, and thus have shorter waveforms than the time slot. Therefore, when filtering using a narrower filter than the magnified OFDM subcarrier width, namely corresponding to the data rate, the waveform will broaden, but only to fill out the timeslot. This means that the bit symbols will not overlap in time and will not introduce inter-symbol-interference (ISI).

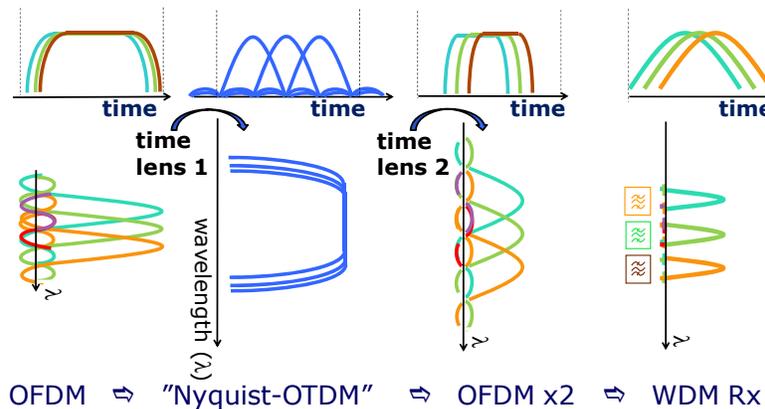


Fig. 2. Principle of OFDM spectral magnification using two time-lenses, followed by optical band-pass filtering for subcarrier detection. In this figure, a magnification of 2 is sketched.

Figure 3 shows simulation results of the basic principle. The simulation is using parameters very close to what is obtainable in the experiment described below. However in the case here, only 5 subcarriers are considered, in order to better see the effect of the time lenses on individual pulses. Each subcarrier is running at 10 Gbaud with 12.5 GHz sinc spectra, 12.5 GHz spacing, and with DBPSK data modulation. Figure 3(top) shows the equivalent spatial telescopic arrangement, with a magnification factor given by the ratio of the focal lengths of the two lenses used, corresponding to the ratio of the spatial parabolic phase modulation from the two lenses. Similarly, the magnification factor for the time lenses is given by the ratio of the phase modulation imposed by the phase modulators, i.e. the chirp rate [16]. Referring to Fig. 3, the magnification becomes: $M = -C_2/C_1$. In Fig. 3, the input OFDM signal is sent through a phase modulator, imposing a chirp rate of C_1 followed by dispersion D_1 . This results in a Fourier transformation in the focal plane, where the OFDM signal is

converted into a serial signal with short optical sinc-like pulses in the time domain (Fig. 3 lowest middle). This signal is now sent through the second time lens, consisting of dispersion D_2 and phase modulation C_2 . This now yields the magnified OFDM spectrum, and correspondingly narrower waveforms of each symbol in the time domain (lowest right).

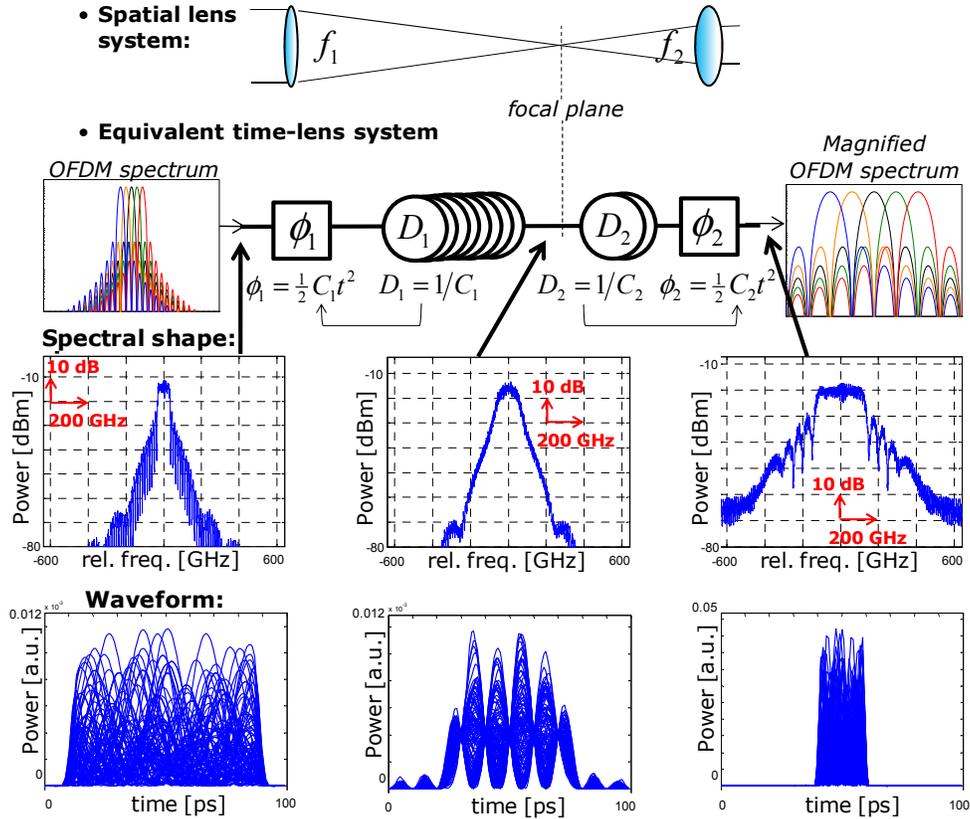


Fig. 3. Simulations of the principle of OFDM spectral magnification using two time-lenses. Top: Equivalent spatial lens telescope system compared to temporal lens system consisting of two phase modulators and two dispersive elements, yielding spectral magnification. Bottom graphs: Spectral and temporal (lowest) shapes at various points through the system as obtained by simulations. Left: Original OFDM signal input to the system. Middle: After the first time lens, corresponding to the focal plane, essentially yielding a parallel-to-serial conversion, i.e. short serial pulses. Right: After the second time lens, where the OFDM spectrum is now restored, but with a 4 times magnification. The temporal symbols are equally narrower.

The next step is now to separate the individual subcarriers using passive filtering. This is shown by simulations in Fig. 4. Here, a Gaussian filter is used to extract a central 10 Gbit/s DPSK subcarrier from the OFDM signal, consisting of five 12.5 GHz sinc subcarriers with 12.5 GHz spacing. In each situation, the filter bandwidth is tuned to obtain the optimum eye opening. Without spectral magnification, the optimum 3-dB filter bandwidth is 8 GHz, and the corresponding demodulated eye is severely distorted due to strong ICI and ISI (Fig. 4 bottom). After x4 magnification, the optimum filter 3-dB bandwidth is 15 GHz, and the ICI is significantly reduced and a clear and open eye can be observed (Fig. 4 top). Thus, these simulations indicate that the suggested scheme operates well.

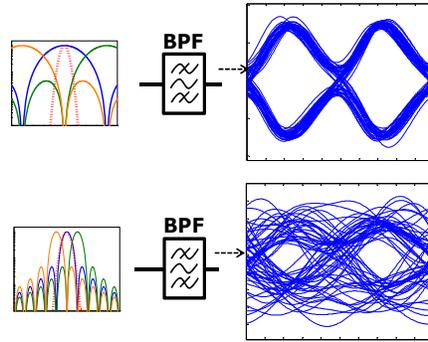


Fig. 4. Simulation results of Gaussian bandpass filtering on the original and magnified OFDM signal. Top: Demodulated eye diagram of 10 Gbit/s DPSK subcarrier filtered with a 15 GHz wide Gaussian filter from an OFDM super-channel with spectral magnification x4 using time-lenses. Bottom: 8 GHz Gaussian bandpass filtering on the original OFDM signal yielding severe eye closure due to ICI and ISI.

3. Experimental demonstration

To verify the proposed principle, we perform spectral magnification x4 on an emulated 100 Gbit/s OFDM super-channel consisting of ten 10 Gbit/s DPSK subcarriers with 12.5 GHz spacing. The parabolic phase-modulation for the time-lenses is achieved by FWM between the OFDM signal and synchronised, linearly chirped pump pulses [13,15].

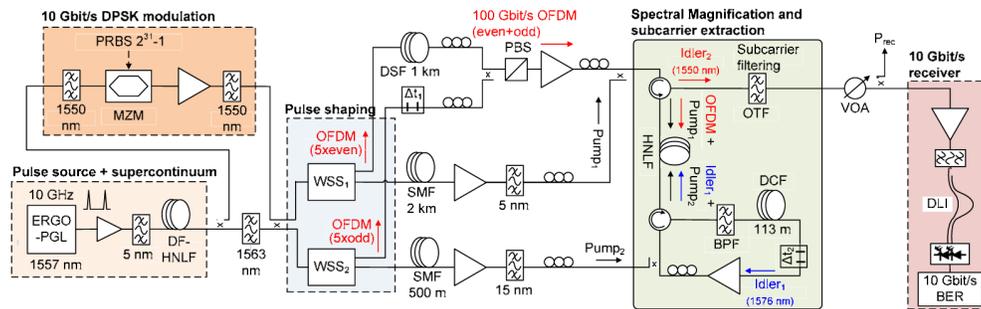


Fig. 5. Experimental setup for x4 spectral magnification and detection of a 100 Gbit/s OFDM superchannel.

The experimental set-up is shown in Fig. 5. The output of a 10 GHz Erbium-glass oscillator pulse generating laser source (ERGO-PGL) at 1557 nm is spectrally broadened by self-phase modulation in a dispersion-flattened highly nonlinear fibre (DF-HNLF). The supercontinuum (SC) thus generated is filtered at 1550 nm using a 5 nm optical bandpass filter (BPF), and the resulting signal is encoded by differential phase-shift keying with a $2^{31}-1$ PRBS. The resulting white spectrum can be sinc-filtered to obtain OFDM subcarriers [8]. To obtain a signal for pump generation, the SC is BPF-filtered around 1563 nm. Both aforementioned signals are recombined and sent to two wavelength selective switches WSS1 and WSS2 (Finisar Waveshaper 4000S) for pulse shaping. The OFDM signal is emulated by separately generating even and odd subcarriers, each consisting of five 12.5 GHz sinc functions with 25 GHz spacing. The sign is reversed between neighbouring sinc subcarriers (for both even and odd), in order to overcome the limited WSS resolution of ~ 10 GHz and thus obtain the highest possible contrast ratio in the generated sinc spectra. The even OFDM subcarriers and the pump signal for the first time-lens (pump1) are generated in WSS1, and the odd OFDM subcarriers and the pump signal for the second time-lens (pump2) are generated in WSS2. Pump1 and pump2 are chirped using 2 km and 0.5 km SMF, respectively, resulting in a x4 spectral magnification. Note that this way of generating the pumps from the

same source as the data signal is not a requirement for this scheme, but merely done to save on lasers in the experiment. In practice, the data transmitter and the magnifier will be separate, and this is fine for the principle. The even and odd subcarriers are de-correlated using a 1 km dispersion shifted fibre (DSF), bit-wise synchronised and recombined in the same polarisation using a polarising beam splitter (PBS). To reduce the number of active nonlinear devices, the FWM processes for the two time-lenses are achieved in a single HNLF using a counter-propagation scheme, where in- and outgoing signals are separated using circulators. The HNLF has a length of 500 m, zero-dispersion wavelength 1561 nm and dispersion slope 0.017 ps/nm²km, and nonlinear coefficient $\sim 10 \text{ W}^{-1}\text{km}^{-1}$.

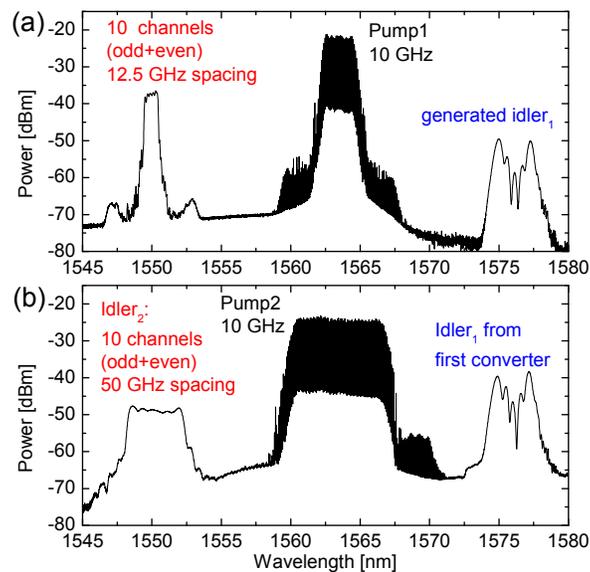


Fig. 6. Optical spectra after the first (a) and second (b) time-lens FWM process in the HNLF.

The HNLF output spectrum resulting from the FWM between pump1 and the OFDM signal is shown in Fig. 6(a). The idler signal at 1576 nm is filtered out using a BPF, and propagated through a 113 m dispersion-compensating fibre (DCF). The signal is then combined with pump2 and coupled into the HNLF for the second FWM process. The resulting spectrum is shown in Fig. 6(b). The generated idler is the output OFDM spectrum, magnified by a factor 4 compared to the input. Figures 7(a) and 7(b) show the original and magnified OFDM spectrum for the even and odd subcarriers, respectively, revealing a good resemblance. The subcarriers are individually filtered out using an optical tunable filter (Santec OTF-350), with a Gaussian profile of 0.12 nm full-width at half maximum (FWHM). The bit-error rate (BER) performance is measured in a 10 Gbit/s pre-amplified DPSK receiver with a 10 GHz delay interferometer (DLI) and balanced photo-detection. For reference, the subcarriers of the original OFDM signal are filtered out using the OTF tuned to the optimum 0.08 nm FWHM (B2B). The resulting 10 Gbit/s DPSK BER curves are plotted in Figs. 8(a) and 8(b), and the corresponding sensitivities (P_{rec} at BER = 10E-9) are plotted in Fig. 9(left). All subcarriers are successfully measured to have BER performance better than 10E-9. Surprisingly, even in the B2B case BER < 10E-9 is obtained. This, however, partly originates in the sign reversal we were forced to employ between every other carrier in both the even and odd subcarriers to achieve a high enough contrast of the sinc spectra. Note also that the utilization of even/odd subcarriers strongly underestimates the cross-talk compared to an OFDM signal with fully de-correlated subcarriers [17]. However, even for this situation, the spectral magnification leads to an improvement in sensitivity from 0.9 to 4.1 dB for all subcarriers except for the two outermost subcarriers (ID -4 and +5). The penalties for ID -4

and + 5 is attributed to increased cross-talk from the neighbour subcarriers, due to some spectral distortion introduced by the time-lenses as indicated by the arrows in Fig. 9(right). Improved performance is expected with better optimized pump signals and larger FWM bandwidth.

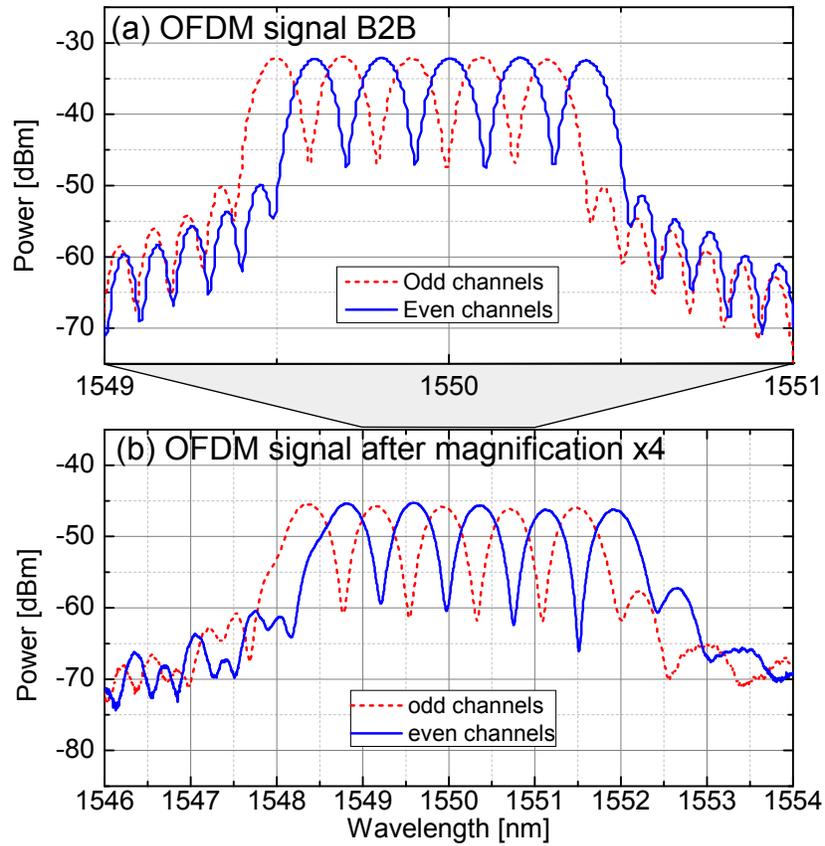


Fig. 7. Optical spectrum of the OFDM signal, (a) before, and (b) after the spectral magnification (x4). The even and odd subcarriers are shown for clarity.

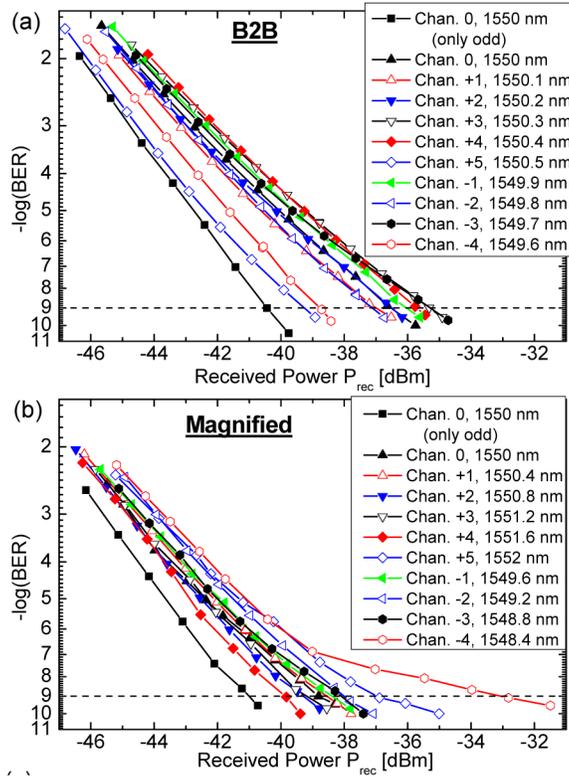


Fig. 8. BER performance of the filtered 10 Gbit/s DPSK subcarriers. (a) B2B case. (b) After 4x spectral magnification. Received power is measured after the sub-carrier filtering, just before the pre-amplified receiver, see Fig. 5.

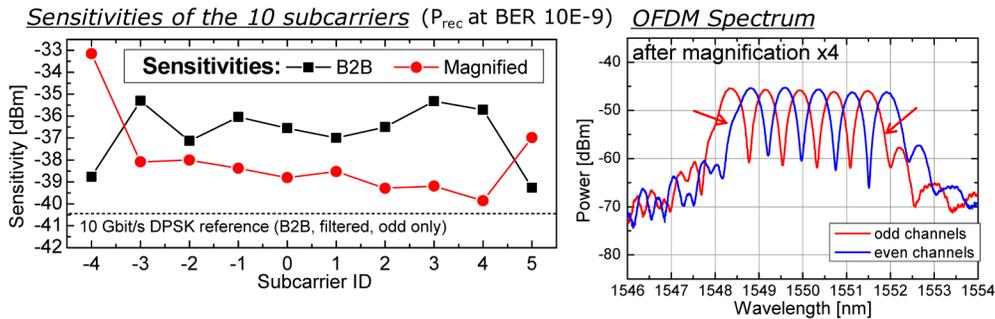


Fig. 9. BER power sensitivities of all subcarriers b2b and magnified (left) and corresponding spectrum (right), shown as odd/even carriers separately to enable visibility of individual channels. The two impaired carriers are clearly identified as the two outermost carriers, which are suffering from some spectral distortion and broadening of their neighbour carriers, resulting in more inter-carrier crosstalk.

5. Discussion and further work

In the above experiment, the tuneable filter used to receive the magnified OFDM signal has a Gaussian shape and a 0.12 nm FWHM. The carriers are magnified to be 50 GHz apart. The idea is that these magnified carriers could be detected by a standard WDM receiver, such as an arrayed waveguide grating (AWG). The best fit for this system would be a 12.5 GHz channel spacing AWG, where only every fourth channel is used. These are commercially

available today with e.g. 48-128 channels [18,19], of which 12-32 outputs could be used to receive 12-32 OFDM carriers after spectral magnification.

The proposed scheme relies on magnifying the OFDM spectrum by a factor M (here $M = 4$), and then using a bandpass filter with a bandwidth comparable to the symbol rate to extract the OFDM signal. This intrinsically implies throwing away about $1-1/M$ of the signal power (here $3/4$), with M being the magnification factor. However, this can be compared to O-FFT (DFT) which requires the use of optical gates following a matched filter as in e.g [7,20], where the gate will carve away $1-T_g/T = 1-1/N$ of the signal power, where $T_g = T/N$ is the allowed gating window width, T the symbol period, and N the number of samples (outputs of the delay interferometer DFT unit). In e.g [7], $N = 8$, and hence $1-T_g/T = 7/8$ of the signal power would be lost. Note, however, that the insertion of a guard interval allows a broader gating window to be used (although the guard interval reduces the spectral efficiency). So the proposed scheme is comparable to previous suggested schemes based on O-DFT as the power loss related to filtering/gating can be of the same order of magnitude. The implication of this on the transmission power budget is under investigation in further studies. As the main idea is to replace the O-DFT receiver, further studies are also under way to more rigorously compare the performance of these two schemes, in terms of OSNR sensitivity and power consumption. The proposed scheme will only use one active magnifier compared to the same number of active gates as number of subcarriers in the O-DFT scheme. On the other hand, the magnifier will require high-power EDFAs, where the gates could be low-power electroabsorption modulators. In [7], 325 sub-carriers were used, though, so a considerable amount of driving power must be expected, whereas a single magnifier could still in principle handle all 325 carriers with only two pump lasers, so the magnification scheme scales favourably. To make a direct meaningful comparison of power consumption, though, is beyond the scope of this paper, as this would require information not readily available in the literature. Another interesting possible limitation of the magnification scheme is that it could result in a lower OSNR sensitivity due to the $1-1/M$ loss of signal power. All of this is subject to further investigation.

6. Conclusion

We have proposed a new scheme for AO-OFDM demultiplexing based on spectral magnification with time-lenses, enabling significantly reduced ICI after simple optical bandpass filtering. The experimental proof-of-principle demonstration confirms that improved BER performance is obtainable after spectral magnification. This scheme allows for the use of standard DWDM receivers to detect spectrally advanced OFDM signals.

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