Spectral mapping using FWM follows the simple formula for the generated idler frequency: \( \omega_i = 2 \omega_p - \omega_s \). Thus using a chirped pump (at frequency \( \omega_p \)), i.e. a tilted waveform in the spectrographic representation in Fig. 1, will map signal frequencies (\( \omega_s \)) to idler frequencies (\( \omega_i \)), in a pulse twice as chirped as the pump. The generated frequencies will be mapped linearly by dispersion as \( \Delta \tau = \Delta \omega D \). Using these simple representations, it is easy to see how optical signals may be manipulated. Fig. 1 shows spectral magnification to twice the frequency separation.

**Figure 1.** Spectrographic description of time lens based WDM grid manipulation utilizing a spectral telescopic arrangement with two time lenses (here, two four-wave mixing units) and dispersion units. The steps include parallel-to-serial conversion in a first time lens followed by serial-to-parallel conversion in a second time lens. The chirp rate ratio between the two time lenses (or equivalently the matched accumulated dispersion \( D = \beta_2 L \)) determines the spectral magnification factor, \( M = D_1/D_2 \).
2. APPLICATIONS

Figure 2 shows a number of advanced applications using time lenses, with a focus on how these manipulations relate to legacy WDM transceivers.

As seen in Fig. 2, it is possible to use currently installed WDM transmitters and receivers and e.g. convert to other formats in between them. For instance, Fig. 2 a) shows how a serial signal may be converted to a parallel WDM signal in order to take advantage of the simpler and more energy-efficient WDM receiver. As discussed in [1], this scenario can be used to create highly energy-efficient communication systems, relying on a low-energy serial transmitter using only a single laser source, and adapting the signal to a WDM receiver using a single time lens unit. The main idea behind this approach is to replace several power-hungry parallel devices with a single ultra-broadband device. In Fig. 2 b), a principle for WDM regeneration is presented. Again, the idea is to use a single broadband regenerator as opposed to individual regenerators for each WDM channel. The key to do this, is to first convert the WDM signal to a single serial channel (parallel-to-serial conversion) in a time-lens unit. As the optical signal processing schemes suggested for optical regeneration are mostly based on ultra-fast optical effects, it is straightforward to perform regeneration on a single ultra-fast serial channel, but very challenging to treat several parallel WDM channels in the same unit. After regeneration the serial signal may be converted back to a WDM signal again and re-transmitted before being received in a WDM receiver [14]. Converting from parallel to serial and back again also implies the possibility of converting with different chirp.
rates. This will e.g. bring the WDM signal back to a different channel grid \[15\], i.e. frequency separation, Fig. 1 and 2 c). In figures 1&2, examples of spectral compression are shown, but it may equally be for spectral magnification, making it truly flexi-grid. Fig. 2 d) and e) show examples of taking a standard WDM signal and converting it to very spectrally efficient data formats. In Fig. 2 d), the WDM signal is converted to a single Nyquist channel (Nyquist OTDM) \[16\], i.e. where there are no guardbands within the spectral extent of the channel and orthogonal sinc-pulses in the time domain, yielding a pure binary spectral efficiency of 1. In \[17\], a 1.28 Tbaud Nyquist channel is created and a time lens based receiver is used to separate the individual channels again. In Fig. 2 e), the WDM signal is converted to an orthogonal frequency division multiplexed (OFDM) signal, with sinc-spectra and rectangular pulses \[18\] and subsequently back to a WDM signal again \[19\]. The latter will also have a potential for power reduction, as an all-optical (AO) OFDM receiver usually requires as many active gates as there are OFDM channels. These types of conversions may be very useful if one needs to upgrade ones WDM legacy installed links to higher spectral efficiency. Finally Fig. 2 f) addresses the fact that there are two main approaches being considered for deployment of spectrally efficient data signals, OFDM and Nyquist WDM. If both of these are installed, using a time lens unit will make it possible to directly convert between the two formats, ensuring full transparency in the optical domain \[20\]. Most time lens implementations have been based on FWM in highly nonlinear fibre (HNLF), giving a high conversion efficiency. Using photonic integrated nonlinear devices such as silicon nano-waveguides have been suggested and demonstrated \[10, 21\], with the advantage of offering ultra-high bandwidth, however with low conversion efficiency. Recently, an AlGaAs-on-insulator nano-waveguide was demonstrated with high conversion efficiency and broad bandwidth \[22\] capable of processing a 1.28 Tbaud data signal.

### 3. SUMMARY

In this paper, an overview of advanced optical signal processing schemes based on optical time lenses have been presented. In particular, a focus has been given to the prospects of using legacy WDM transceivers in combination with time lens units to upgrade to more spectrally efficient data formats, more power efficient systems, or to perform WDM regeneration or WDM flex-grid operations. Time lenses offer many possibilities for advanced optical signal processing, and as more efficient nonlinear platforms are being developed, such as AlGaAs nano-waveguides, more practical implementations of time lens telescopic units become promising for future developments.

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