

WDM Wavelength Quantizer

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Abstract: We demonstrate a novel all-optical frequency shifter that remaps signals with significant unknown frequency drifts onto precise static frequencies, as defined by channel multiplexing filters. We show <1 dB sensitivity penalty for frequency remapping with channel detuning of ± 5 GHz.

OCIS codes: (190.4223) Nonlinear wave mixing; (320.5540) Pulse shaping;

Introduction

As passive-optical networks increase their penetration in access networks [1], the interfaces between optical networks of different scales become important in overall network operation. At the access side, the user's optical interface is extremely cost sensitive, often requiring sacrifices in system performance. Conversely, as the demands on capacity at the metro and long-haul continue to increase, higher precision components are required to optimize overall system capacity.

As illustrated in Fig. 1, interfacing these different networks, while keeping the signals in the optical domain, is problematic. The frequency grid used for wavelength division multiplexing (WDM) is tightly specified, requiring frequency stabilization of the transmit lasers used in this system, while in access networks, lasers may run without temperature control or precise frequency tuning, resulting in significant drifts in optical frequency.

Currently, aggregation of access network connections onto higher capacity networks is achieved through optical-electronic-optical (O-E-O) conversions. This provides for signal regeneration and wavelength conversion, to make the incoming signal compatible with the WDM grid on the high-capacity side. O-E-O conversion does, however, introduce system latency in the conversion process and occupy high-demand rack space with its high-speed electronic interfaces.

In this paper we propose utilizing optical sampling that uses a pump with multiple comb lines (Fig. 2), followed by optical filtering with arbitrary center frequency to quantize a randomly drifting incoming optical signal to the desired WDM grid. This is in contrast to most wavelength conversion methods, which require known signal frequencies [2] or significant and controlled signal-carrier frequency offset [3].

In our experimental demonstration, the sampling is achieved by mixing a train of short optical pulses (a wide-bandwidth comb in the spectral domain) with a narrowband signal. The resulting broad-band signal can be filtered to match a WDM grid with a small (<1 dB) performance penalty. We demonstrate the system with 10-Gbps on-off keyed (OOK) signals, sampled using nonlinear optical frequency conversion in a periodically poled lithium niobate waveguide. We show that the optical sampling is able to shift the input frequencies by at least the channel bandwidth.

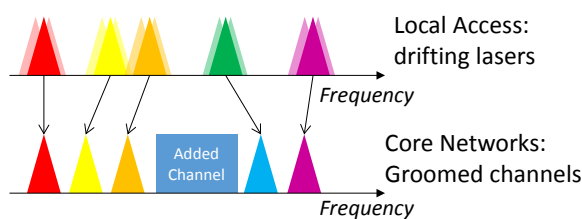


Fig. 1: Grooming Access wavelengths onto a Core network.

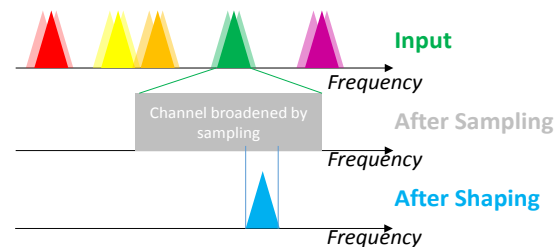


Fig. 2: All-optical grooming by sampling and shaping.

Principle of optical arbitrary frequency shifting

As illustrated in Fig. 2, the mixing of the short optical pulses and the signal results in a “white” spectrum [4], when the baud rate of the signal is the same as repetition rate of the sampling. This white spectrum can then be optically filtered (or pulse shaped) to generate a signal at the desired frequency. We have previously shown that commercial wavelength-selective switches are able to reshape modulated pulses to provide almost any signaling format, such as optical OFDM, Nyquist-WDM, Optical Time Division Multiplexing (OTDM) and WDM [4].

In this work, the “white” spectrum can be optically filtered anywhere within its spectral extent, regardless of center frequencies of the comb lines associated with the short optical pulses, to generate a new signal at the desired optical frequency. As such, if the signal laser is drifting, the optical channel filter (provided by a wavelength selective switch for instance) can ensure that the desired center frequency has been filtered out. Furthermore, the resulting center frequency can be changed by simply changing the optical channel filter.

Experimental Setup and Results

The experimental setup (Fig. 3) consists of an optical pulse source, on-off keyed transmitter, optical sampler, channel filter, and direct-detection receiver. The pulse source operates at 193.3 THz, with pulses generated from a CW wave followed by intensity (IM) and phase (PM) modulators driven by a 10-GHz sinusoid [5]. The phase modulator is driven via a 29-dBm RF amplifier, and provides the majority of the spectral broadening. A wavelength selective switch (WSS) compresses the pulses by applying a quadratic spectral phase filter and flattens the spectrum through line-by-line attenuation [6], producing a 90-GHz wide, flat-top spectrum (inset, Fig. 3). The pulse average power is amplified to 1.45 W and combined with the signal with a WDM coupler, which additionally filters the pulses with a 100-GHz bandpass filter. The transmitter provides a signal centered at 193.1 THz, that is NRZ-OOK modulated with a $2^{15}-1$ binary PRBS sequence at 10 Gbaud, and is delayed by variable optical delay line to temporally align the signal with pump sampling pulses. The optical sampler is a 50-mm long periodically poled lithium niobate (PPLN) waveguide, where difference frequency generation (DFG) allows the generation of a phase-conjugate sampled signal at a different wavelength [7, 8, 9], commonly called the idler. The polarization controllers (PCs) are used to align the polarizations of the signal and pump to maximize the output idler power. Fig. 4 is the spectrum of the PPLN output. After the PPLN chip, the high-power pump is attenuated by a WDM coupler. A WSS filter with 170-GHz bandwidth and 193.5-THz center frequency is then used to select the sampled signal (or ‘idler’) as the output from the sampler.

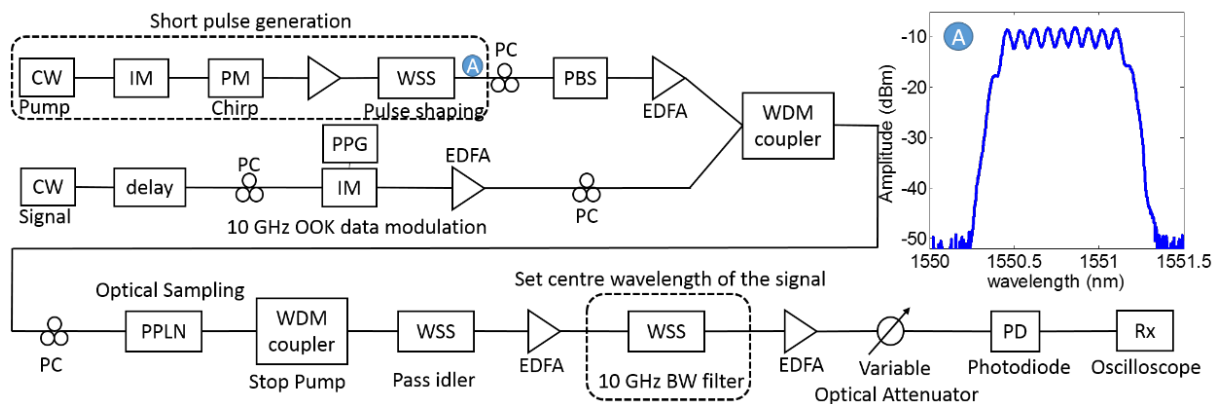


Fig. 3: Experimental setup. EDFA: Erbium doped fiber amplifier. PPG: Pulse pattern generator. PBS: Polarization beam splitter.

The sampled signal is amplified, then filtered with a 10-GHz bandwidth ‘channel’ filter. The filter’s center frequency is changed to simulate the frequency drifting effect of the signal laser. This is equivalent to the transmit laser’s frequency drift, as the conversion efficiency of the chip is flat over the 10-GHz tuning range used, owing to the THz-wide phase matching bandwidth for DFG in the PPLN chip [9].

The receiver comprises a 40-GHz bandwidth photo-receiver with an internal trans-impedance amplifier (Finisar XPRV2021A), with the output digitized by a 40-GSa/s, 16-GHz bandwidth real-time oscilloscope. The received waveforms are stored and analyzed offline for error counting. The received power level is controlled via a variable optical attenuator.

The bit-error ratio (BER) is plotted against received power in Fig. 5, for various central frequencies. In this experiment, we assume that the system will be running with a 7% overhead, RS{255,239} forward error correction code (FEC) to bring a pre-FEC measured bit-error rate down from 3.8×10^{-3} to an error-free level of 1×10^{-15} . As such, the receiver’s sensitivity is defined as the received power at a BER = 3.8×10^{-3} . We take the measured performance of the modulated continuous wave (CW) signal passed directly into the receiver as a ‘back-to-back’ benchmark (magenta circles Fig. 5). This gives a receiver sensitivity of -20.9 dBm.

The curves for the idler filtered at various center frequencies by a 10-GHz bandwidth channel filter are shown in red in Fig. 5. The receiver sensitivity varies between -20.7 and -20 dBm, corresponding to a performance penalty compared with the modulated CW wave of between 0.2 and 0.9 dB. In order to investigate the penalty introduced by the mixing process in the PPLN chip, the pump is modulated in the same manner as the case of a CW input, then

filtered by 10-GHz bandwidth filter (blue traces in Fig. 4). For the modulated pump, the receiver sensitivities are -20.8 to -20.6 dBm, corresponding to penalties of 0.1 to 0.3 dB.

The average sensitivities of the filtered idlers and modulated pump are -20.4 dBm and -20.7 dBm, respectively. The additional 0.3-dB sensitivity penalty may be due to spectral shaping of the idler away from the ideal white spectrum, or through noise introduced by the amplifiers before and after the PPLN. The spread in BER curves of idlers (± 0.4 dB in sensitivity) further points to spectral shaping as a prime cause of penalty, as the modulated pump spread is much less (± 0.1 dB sensitivity spread).

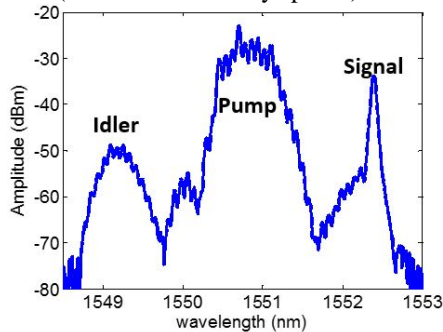
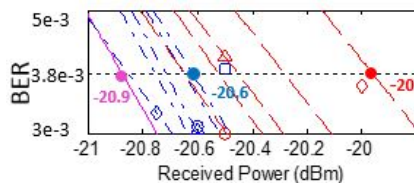


Fig. 4: C-band spectrum at the output of PPLN chip.



Zoom in of Fig. 5, showing maximum required received power for modulated pulse (blue) and sampled (red) signal, relative to the CW reference (pink).

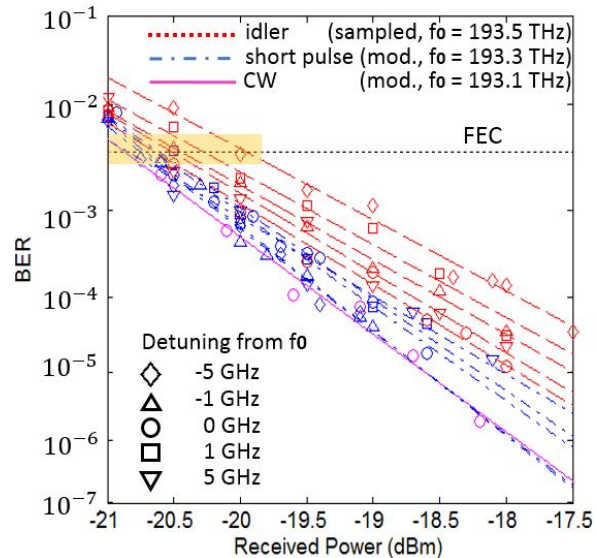


Fig. 5: BER vs. Received Power for modulated CW, modulated short pulse and idler.

The sampler used for this function must be synchronized to the clock of the incoming signal. This can be achieved in synchronous systems, or through a clock recovery/synchronization stage [10], at the expense of some electronic control. While here we show arbitrary frequency shifting for a single wavelength, the large available conversion bandwidth of PPLN devices would allow for the re-quantization of multiple wavelength channels to a WDM grid simultaneously, increasing the efficacy of this device. Moreover, by using a chip-based nonlinear device, this system has the potential to be a compact addition to racks. With higher conversion efficiency sampling [11], the amplifiers used in this set-up may be avoided.

Conclusions

We have experimental demonstrated an all-optical arbitrary frequency shifter based on optical sampling. The proposed scheme provides a solution to laser drift when connecting access networks to core networks, and allows the output frequency to be defined by a channel multiplexing filter or wavelength selective switch. The power penalty when frequency re-quantizing a 10 Gbps OOK signal is <1 dB.

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