Tunable optical wavelength conversion of OFDM signal using a periodically-poled lithium niobate waveguide

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Abstract: We experimentally demonstrate tunable optical wavelength conversion of a 10-Gb/s radio frequency (RF)-tone assisted orthogonal-frequency-division-multiplexing (OFDM) signal with ~-5 dB (~30%) efficiency over ~30 nm bandwidth using a periodically-poled lithium-niobate (PPLN) waveguide. A penalty of < 3 dB is obtained after wavelength conversion. Quadrature amplitude modulation (QAM) size and subcarrier number are varied to further evaluate the performance of the wavelength converter.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) modulation; (190.7110) ultrafast nonlinear optics.

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1. Introduction

Optical orthogonal-frequency-division-multiplexing (OFDM) has gained much interest in the optical fiber communication community due to its robustness to various channel degrading effects as well as efficient use of the spectrum. These advantages result from using powerful post-processing techniques after detection and thus enable long distance, uncompensated transmission systems [1–3]. In a wavelength-division multiplexing (WDM) network, it would be desirable that the OFDM data channel can transparently traverse many wavelength-selective elements in order to avoid inefficient optical-to-electronic conversions. One impediment to fully utilize transparency is the ability to rapidly resolve output-port contention.

As has been well documented, optical wavelength conversion of a data channel can effectively resolve contention and dramatically increase network throughput. Optical wavelength conversion has been demonstrated for most types of data modulation formats and using many types of wavelength conversion techniques [4–6]. A key goal in any future WDM network is for the conversion approach to enable data format transparency, as well as to be broadband, high-speed, low chirp, low additive noise, efficient, and high data extinction ratio.

One method for wavelength conversion that has shown many of these characteristics is the periodically-poled lithium-niobate (PPLN) waveguide [7], which has been used to convert baseband data that is encoded in amplitude and phase. However, we are not aware of any wavelength conversion of OFDM data channels.

In this paper, we experimentally demonstrate tunable optical wavelength conversion of a 10-Gb/s radio frequency (RF)-tone assisted OFDM signal using a PPLN waveguide. The combination of sum frequency generation (SFG) and difference frequency generation (DFG) nonlinear processes in a PPLN waveguide is exploited. Bit-error rate (BER) measurements are performed after wavelength conversion. Quadrature amplitude modulation (QAM) size and subcarrier number are further varied to evaluate the performance of the wavelength conversion scheme.

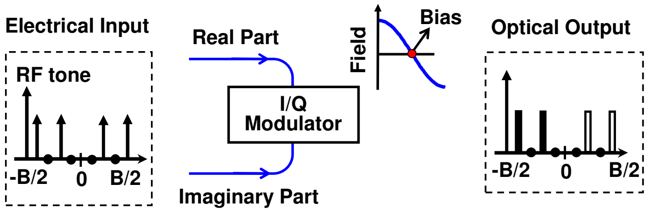

Fig. 1. Concept of radio frequency (RF)-tone assisted OFDM. B: bandwidth of the OFDM signal.

2. Concept

2.1 RF-tone assisted OFDM

Figure 1 shows the schematic approach for generating the RF-tone assisted OFDM. The electrical subcarriers are assigned for the data symbols, blank symbols, and one inserted RF tone as the amplitude and phase reference for direct detection. The data symbols are allocated on the even-numbered subcarriers while the blank symbols are on the odd-numbered subcarriers, and thus the data and the blank subcarriers are arranged in an interleaved manner. The RF tone is placed at the left- or right-most odd-numbered subcarrier such that the lower or upper single sideband format (SSB) can be generated. The signal generated in frequency domain is then converted to the OFDM waveform in time-domain by use of inverse fast Fourier transform (IFFT). The real and imaginary parts of the complex OFDM signal are then sent to the in-phase (I) and quadrature-phase (Q) arms of an optical I/Q modulator, which is

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biased at the null to suppress the original optical carrier. The modulated optical OFDM signal has a similar spectrum as its electrical counterpart and has a SSB format. Since the signal is linear field-modulated, the signal-signal beat interference (SSBI) may be introduced to the received signal [8] and thus result in system power penalty. Due to the interleaved manner of our proposed RF-tone assisted OFDM, the SSBI falls between the data subcarriers, i.e. the blank carriers, and therefore does not interfere with the data. The data information can be recovered by the channel equalizer without being interfered by the SSBI.

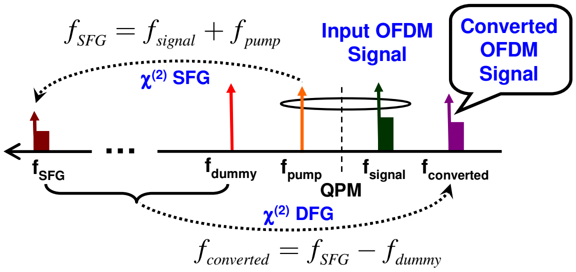

Fig. 2. Concept of wavelength conversion using the combination of sum frequency generation (SFG) and difference frequency generation (DFG) in a PPLN waveguide. QPM: quasi-phase matching.

2.2 *PPLN-based wavelength conversion*

Shown in Fig. 2 is a conceptual block diagram of tunable wavelength conversion using a PPLN waveguide in a two pump configuration. An input signal (f_{signal}) nonlinearly interacts with a continuous wave (CW) light (f_{pump}), and SFG occurs under the quasi-phase matching (QPM) condition that can be set through the waveguide temperature controller. The generated signal (f_{SFG}) simultaneously interacts with another CW light (f_{dummy}) to produce the converted signal ($f_{converted}$) in C-band through the DFG process. The converted wavelength can be tuned through the tuning of the dummy signal wavelength (f_{dummy}).

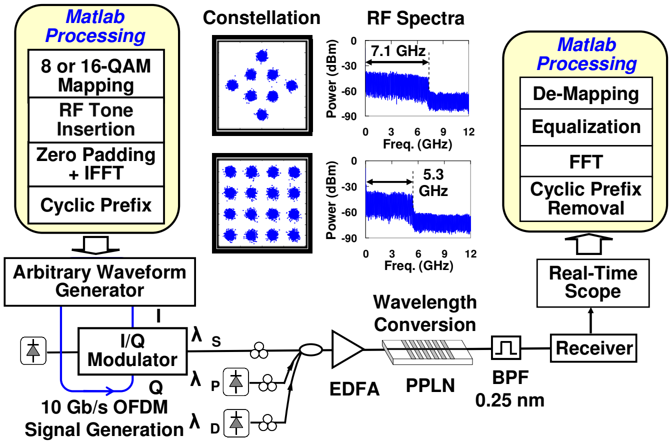

Fig. 3. Experimental setup of OFDM wavelength conversion. The constellations and RF spectra of 8-QAM & 16-QAM are inserted. BPF: band-pass filter.

3. Experimental setup

Figure 3 shows the experimental setup. The interleaved RF-tone assisted 10-Gb/s OFDM signal is generated by Matlab program offline [8,9]. The input 10-Gb/s data is first mapped onto QAM symbols, the size of which is variable (8-QAM or 16-QAM) in our experiment. Subsequently, 92 subcarriers for the QAM symbols and one subcarrier for the RF tone are zero-padded with an IFFT size of 256 and then converted to the time-domain waveform by

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use of IFFT. A cyclic prefix of 1/16 of the symbol duration is applied for the margin of synchronization offsets and the inter-symbol interference. The OFDM signal generated by Matlab is then loaded into an arbitrary waveform generator (Tektronix, AWG7102) with a sampling rate of 10 GHz. The two outputs of the AWG, which are the real and imaginary parts of the OFDM signal, are low-pass filtered to remove the out-of-band residual image interference [9] and then sent into the two arms of an optical I/Q modulator, respectively. Since the PPLN waveguide requires polarization aligned signals at its input, the modulated optical OFDM signal, the pump and the dummy are controlled by separate polarization controllers (PC) before combined together. The combined signals are then amplified by an erbium doped fiber amplifier (EDFA) before being sent to the PPLN waveguide. The converted signal is filtered out by a 0.25 nm band pass filter (BPF) and then sent to a variable optical attenuator and an EDFA to adjust the received optical signal-to-noise ratio (OSNR), followed by another 0.25 nm BPF before detection. The received electrical signal is then sampled at 20 GSample/s by a real time scope (Tektronix, TDS6604) and the stored samples are post-processed in Matlab for synchronization, cyclic prefix removal, fast Fourier transform (FFT) and equalizations.

The insets shown in Fig. 3 are the equalized 8-QAM and 16-QAM constellations and the corresponding RF spectra after the photodiode of the 10-Gb/s RF-tone assisted OFDM signal. The signal bandwidth is about 7.1 GHz for 8-QAM and about 5.3 GHz for 16-QAM.

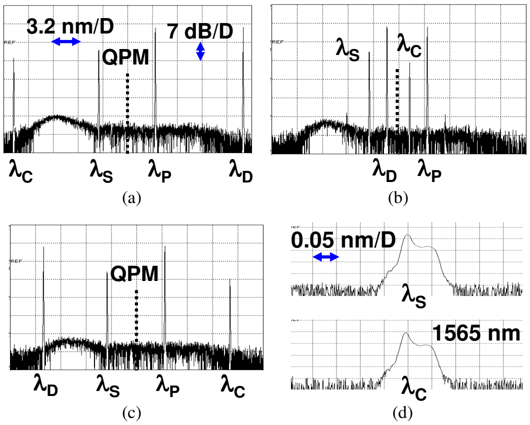

Fig. 4. Optical spectra after wavelength conversion. QPM: quasi-phase matching wavelength. (a) λ_C = 1538.5 nm (b) λ_C = 1554.4 nm (c) λ_C = 1565 nm (d) 10-Gb/s optical OFDM signal (zoomed-in).

4. Results and discussions

Shown in Fig. 4 are the optical spectra after the PPLN at several converted wavelength locations. The PPLN waveguide is temperature controlled to have a QPM location of ~1553 nm. With the signal (λ_S), which is at ~1549.5 nm, and pump (λ_P), at ~1556.5 nm, symmetrical to the QPM wavelength, the signal is converted to 1538.5 nm, 1554.4 nm and 1565 nm (λ_C) by placing the dummy (λ_D) at ~1567.5 nm, ~1551.6 nm and ~1541 nm, respectively, as shown in Fig. 4 (a)~(c). The power levels of the input signal, pump and dummy are ~13 dBm, ~21 dBm, and ~21 dBm, respectively. By tuning the dummy wavelength, we observe the conversion efficiency is ~-5 dB (~30%) over ~30 nm bandwidth, relative to the input signal power into the PPLN. The 30 nm conversion bandwidth is mainly limited by the EDFA bandwidth. Note that the converted wavelength cannot be generated at the QPM and the pump wavelength. These gaps can be avoided through temperature tuning of the QPM wavelength. The QPM is ~1543 nm at 25 °C and ~1553 nm at 105 °C and it is pretty linear over the tuning range. This range should be enough for the QPM to be tuned to in order to access the whole wavelength conversion range and possibly to avoid having converted signal too close to the QPM wavelength, in which case the converted signal experiences relative large nonlinear

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distortions. Note that the pump wavelength needs to be tuned accordingly. Figure 4 (d) shows the spectra of the input and converted OFDM signals. We observe that the carrier to signal power ratio (CSPR), which has been proved to be optimal at ~0 dB [8], is preserved after the wavelength conversion. This means, after wavelength conversion, the system performance is not degraded by CSPR. Here, we use wavelength instead of frequency (Fig. 2) to represent the signal locations for simplicity. λ_s, λ_P, λ_D, and λ_C correspond to f_{signal}, f_{pump}, f_{dummy}, and $f_{converted}$ in Fig. 2, respectively.

To assess the performance of the wavelength converter, we measure the BER versus OSNR/0.1 nm both back to back and after conversion at different locations. Shown in Fig. 5 are the BER curves and the corresponding 8-QAM and 16-QAM constellations. The OSNR penalty in the conversion range is observed to be 1~3 dB. Approximately 1 dB penalty at 10^{-3} BER is observed at 1538.5 nm and 1565 nm. For the converted signals that are close to the QPM, i.e., 1554.4 nm, we observe a ~3 dB penalty, which could be attributed to the relatively larger nonlinearity as the converted signal approaches to the QPM. Notably, compared with the conventional single-carrier format [10], the converted OFDM signal exhibits slightly larger OSNR penalty caused by the conversion-induced nonlinear distortion [11].

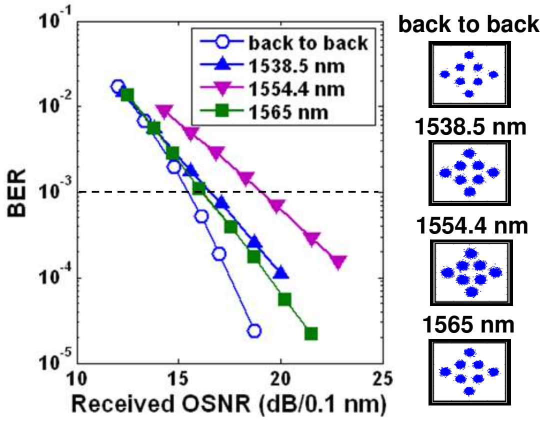

Fig. 5. BER performance of the 10-Gb/s RF-tone assisted OFDM signal for both back to back and after wavelength conversion.

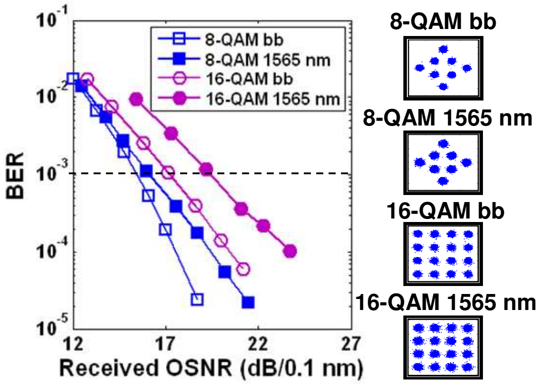

Fig. 6. BER performance of 8-QAM and 16-QAM for both back to back (bb) and after wavelength conversion.

QAM size is varied to evaluate the performance of the wavelength converter. Figure 6 compares the BER performance of 8-QAM and 16-QAM for both back to back and the conversion to 1565 nm. 1565 nm is chosen for illustration purpose since it has relatively small OSNR penalty and the effect of QAM size can possibly be better shown. From Fig. 6, we can see when the QAM size is increased from 8 to 16, the penalty is increased by about 1 dB. The reason could be that OFDM signal with a larger QAM size is more vulnerable to the nonlinear distortion induced during the wavelength conversion. The corresponding constellations of different QAM sizes before and after wavelength conversion are inserted in the figure.

Furthermore, we use different subcarrier numbers, i.e., 92, 184 and 368, with a fixed QAM size (8-QAM) to explore the effect of subcarrier numbers. BER versus OSNR/0.1 nm is shown in Fig. 7 for both back to back and the converted signal at 1565 nm. Again, 1565 nm is chosen for illustration purpose. We observe that the penalty almost keeps the same as we vary the subcarrier numbers, which shows the performance of our wavelength converter is not dependent on the subcarrier numbers.

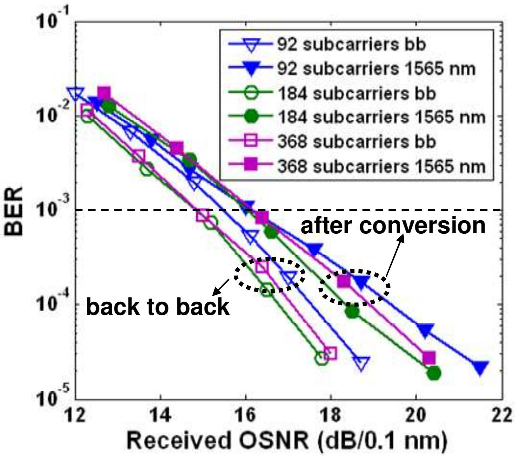

Fig. 7. Effect of different subcarrier numbers on wavelength conversion for a 10-Gb/s RF tone assisted OFDM signal. bb: back to back.

The technique of using the combination of SFG and DFG in PPLN waveguides for OFDM tunable wavelength conversion is shown for a 10-Gb/s RF-tone assisted OFDM signal. We anticipate this approach is also applicable to other OFDM formats, such as double sideband (DSB) OFDM, traditional SSB OFDM and coherent optical OFDM [2]. PPLN waveguides have been shown for all-optical signal processing at up to 320-Gb/s [12]. Our scheme of OFDM wavelength conversion is readily extended for higher bit rate OFDM signals given the wideband signal processing capability of PPLN waveguides.

In addition, what we show experimentally is to obtain a single copy of the signal. In future WDM networks, the function to get multiple copies, so called signal multicasting, would be desirable for routing, etc. By simply adding more dummy CW lights, our scheme is readily extended for OFDM signal multicasting.

5. Conclusion

We experimentally demonstrated tunable optical wavelength conversion of 10-Gb/s RF-tone assisted OFDM signal with ~-5dB conversion efficiency over ~30 nm tuning range using a PPLN waveguide. A penalty of less than 3 dB was obtained after wavelength conversion over the conversion range. QAM size up to 16 and subcarrier number up to 368 were demonstrated. Operating at the one of the best-performing wavelengths, we were able to show less than 1 dB penalty with the variation of the QAM size and subcarrier number, which showed the potential of using PPLN waveguides in converting OFDM signals.

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