Wavelength Conversion of Subcarrier Channels Using Difference Frequency Generation in a PPLN Waveguide

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***Abstract*—The authors demonstrate and characterize a transparent all-optical wavelength conversion process for subcarrier-multiplexed channels. Their memoryless $\chi^{(2)}$: $\chi^{(2)}$ difference-frequency-generation process uses 1550-nm pumping in a periodically poled lithium niobate waveguide. They achieve penalty-free all-optical wavelength conversion of two 55-Mb/s subcarrier channels. The process shows a $>$30-dB linear dynamic range for crosstalk-free transparent operation.**

***Index Terms*—Subcarrier, wavelength conversion.**

FOR MANY applications, it is quite advantageous to transmit several analog or digital subcarrier-multiplexed (SCM) RF channels over an optical fiber link or network. These applications include: cable TV, wireless network interfaces, microwave photonic systems, and control information for optical networking and optical packet switching [1]–[3]. Moreover, subcarrier modulation is important for data grooming, bandwidth allocation flexibility, and access networks.

Next-generation networks may have routing and switching capabilities in the wavelength-division multiplexing (WDM) layer for flexible bandwidth allocation. Reconfiguration can be achieved either by a tunable transmitter or a tunable receiver. In either case, wavelength conversion is needed in order to increase the efficient use of the limited wavelength pool as well as resolve wavelength contentions [4].

It is only natural to envision a future platform that combines subcarrier multiplexing with wavelength conversion for high-throughput network performance. In such a network, wavelength conversion should support signals of arbitrary formats/protocols in order to accommodate various user applications and facilitate network interoperability. All-optical wavelength shifting of subcarrier signals can be accomplished by several methods, including: cross-gain modulation (XGM), cross-phase modulation (XPM), four-wave mixing (FWM), and difference-frequency generation (DFG) [5]–[8]. However, only FWM and DFG offer complete format transparency. Moreover, all methods except DFG generally use a semiconductor optical amplifier (SOA) as their wavelength-shifting medium, which generates at least one of the following disadvantages, depending on the specific method used: 1) distortions due to nonlinear and population-dependent memory characteristics; 2) crosstalk; 3) limited conversion speed; 4) limited wavelength range; 5) limited conversion efficiency; 6) additive noise; 7) spectral distortion; and 8) limited dynamic range. Alternatively, DFG achieves memoryless linear transparent wavelength shifting with extremely low crosstalk and quantum-limited additive noise over a wide wavelength range. Wavelength shifting of subcarrier channels has been demonstrated using DFG in an AlGaAs device [9].

In this letter, we demonstrate and characterize a transparent all-optical wavelength conversion process for subcarrier-multiplexed channels in which a memoryless $\chi^{(2)}$: $\chi^{(2)}$ DFG process uses 1550-nm pumping in a periodically poled lithium niobate (PPLN) waveguide. We achieve penalty-free all-optical wavelength conversion of two 55-Mb/s subcarrier channels, and the process shows a $>$30-dB linear dynamic range for crosstalk-free transparent operation. We note that the PPLN structure has a lower insertion loss than the AlGaAs device in [9].

Fig. 1(a) illustrates the desired wavelength conversion function. Data is imposed on modulated sidebands around an original carrier wavelength λ_1. After wavelength conversion, these same sidebands are located around a new carrier wavelength λ_2. Fig. 1(b) shows a conceptual diagram of the operation of the $\chi^{(2)}$: $\chi^{(2)}$ process used to perform this function [10]. The first $\chi^{(2)}$ process involves the CW pump (λ_{pump}) undergoing second harmonic generation (SHG) to produce a local oscillator at $\lambda_{\text{pump}}/2$. This then mixes with the modulated signal $\lambda_{\text{signal}}(t)$ through DFG to form a wavelength-shifted copy of the signal at a wavelength of $\sim(2\lambda_{\text{pump}} - \lambda_{\text{signal}}(t))$. Both parametric processes are instantaneous, permitting modulation bandwidths in excess of several teraHertz. The conversion efficiency is symmetric in the forward and backward directions. Since the DFG conversion efficiency is not proportional to the signal power, the process is linear over a large dynamic range. Moreover, there is no crosstalk sideband at $(2\lambda_{\text{signal}}(t) - \lambda_{\text{pump}})$ as there is in FWM.

Our experimental setup is shown in Fig. 2. A tunable laser is set at 1555 nm and used as a CW signal. A 55-Mb/s on–off-keyed bit stream is binary-phase-shift-key (BPSK)

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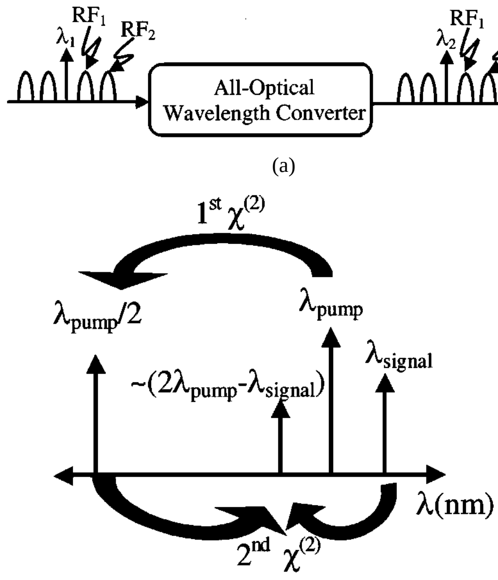

Fig. 1. Conceptual diagram of (a) wavelength conversion of subcarrier channels and (b) DFG in a PPLN waveguide using a $\chi^{(2)}$: $\chi^{(2)}$ process.

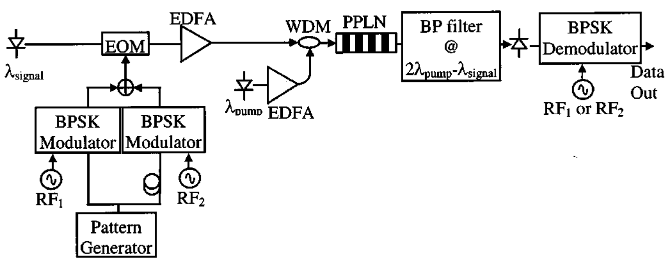

Fig. 2. Experimental setup.

modulated onto an RF_1 carrier at 650 MHz, and a second 55-Mb/s channel is modulated onto an RF_2 carrier at 1050 MHz. The subcarrier channels are fed into a 2-GHz-bandwidth $LiNbO_3$ external modulator. The EDFA is placed after the external modulator and is used to control the signal power launched into the PPLN waveguide. A tunable narrow-linewidth external-cavity laser at 1550 nm is used as the pump source for initiating the DFG process. The 1550-nm pump source is amplified to +22 dBm and fed into a wavelength-selective coupler. This coupler combines the pump and signal and also filters out the amplified-spontaneous-emission noise of the high-power EDFA. At the output of the PPLN waveguide, the wavelength-converted signal at 1545 nm is optically filtered and received. The receiver is connected to a BPSK demodulator to recover the original bit stream. The BPSK demodulator is driven by either a 650- or a 1050-MHz RF carrier to select between the subcarrier channels.

The optical spectrum at the PPLN waveguide output is shown in Fig. 3. The power difference between the 1555-nm original signal and the 1545-nm wavelength-shifted signal at the output of the PPLN waveguide is the conversion efficiency. For a 1550-nm input pump power of ~100 mW, a conversion efficiency of −21 dB is observed. One reason for the low conversion efficiency in this particular device is anomalous loss in the fiber pigtails. Typical fiber-to-fiber insertion loss is 3.5 dB [10], while the device used in this work showed

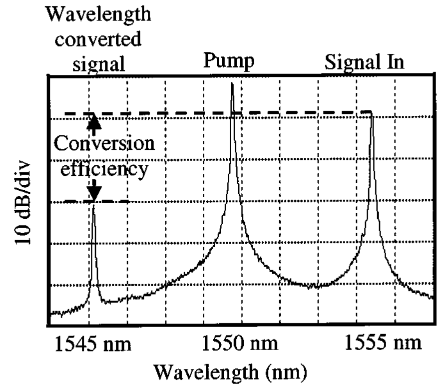

Fig. 3. Optical spectrum after wavelength conversion in the PPLN waveguide.

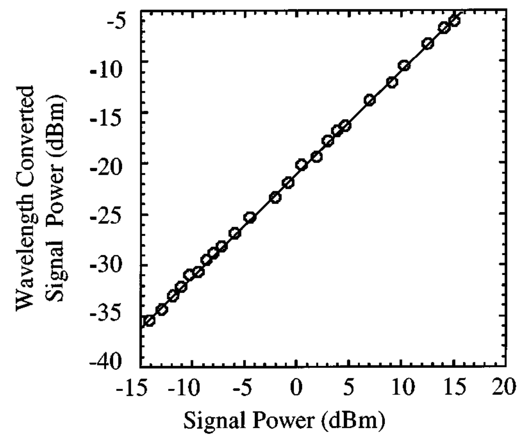

Fig. 4. Linearity of DFG: wavelength converted signal power versus signal power, measured after the PPLN waveguide.

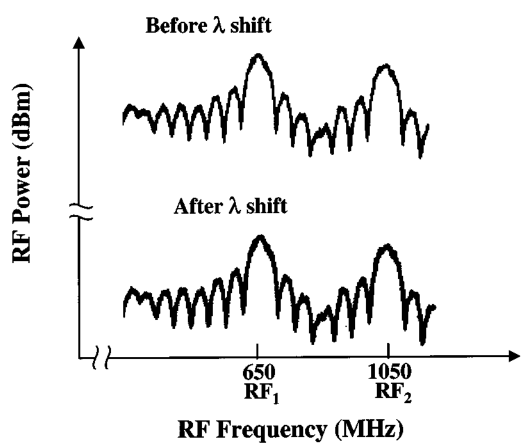

Fig. 5. RF spectra before and after wavelength conversion.

a much higher loss of ~7 dB. It should also be noted that recent demonstration of a novel buried waveguide design and fabrication technique have led to a threefold increase in the internal conversion efficiency [11]. An optimized device using this technique would allow for 0-dB wavelength conversion with only 75-mW pump power.

Fig. 4 shows the variation of the wavelength-shifted output signal power as a function of the input signal power, for which the pump power is kept constant. Wavelength-conversion efficiency of −21 dB is maintained regardless of the input signal power level, demonstrating the large linear dynamic range of

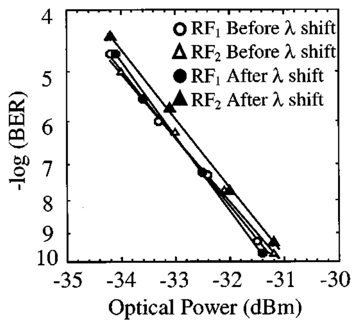

Fig. 6. BER curves of subcarrier multiplexed channels for before and after wavelength conversion.

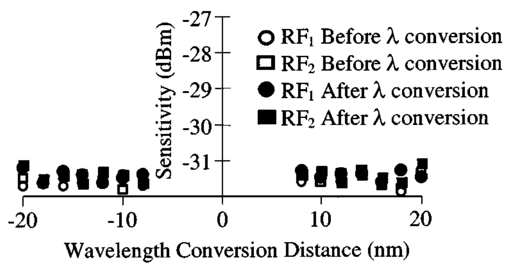

Fig. 7. Received optical power sensitivities for 10^{-9} BER versus wavelength spacing between the input and output data signal.

the DFG process as expected from theory. To further characterize the linearity of the DFG process, we have measured the RF spectra of the subcarrier channels before and after the wavelength-conversion process. As shown in Fig. 5, the spectra are virtually identical, indicating transparent wavelength conversion. In contrast, a nonlinear process would show harmonics and spectral distortion.

Fig. 6 shows the bit-error-rate (BER) curves of the data signals before and after wavelength conversion for both subcarrier channels. No significant power penalty is observed. To measure the effect of the wavelength spacing between the input signal and the pump, the signal wavelength is varied across a broad range. In Fig. 7, receiver sensitivities for 10^{-9} BER in terms of optical power are plotted as a function of the wavelength spacing between the input and output signals (i.e., twice the wavelength difference between the input signal and the pump). For both up- and down-conversion, we observe up to 20-nm wavelength shifts with similar performance, limited only by the EDFA bandwidth and filtering characteristics of our equipment.

In this experiment, within our knowledge, we demonstrate the first parametric wavelength conversion of optically modulated subcarrier channels. By employing the $\chi^{(2)} : \chi^{(2)}$ difference-frequency-generation process, we achieve a large linear dynamic input power range of >30 dB. Throughout the experiment we preserved a wavelength conversion efficiency of -21 dB for our PPLN waveguide, yet recent studies indicate that it is possible to increase this efficiency up to 0 dB. Due to high linearity of this process, we observe no measurable distortion or beating term generation at Rf1 + Rf2 and Rf1 − Rf2 frequencies.

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