Investigation of pump light generation methods and precise all-optical FWM wavelength conversion for wavelength defragmentation

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Abstract: This study investigates pump light generation methods for all-optical wavelength conversion systems using four-wave mixing in highly nonlinear fibers. The number of light sources, combination of sinusoidal signal frequency, and number of cascaded stages of LiNbO₃ phase modulators were compared. As a result, 13 flat optical combs with a 10-GHz frequency spacing were generated with three-stage modulators, and it was confirmed that the noise level of the pump was as small as the seed light source. In the wavelength conversion experiment, a bit error rate of $<10^{-10}$ for the converted signals was obtained in the case of the ±60-GHz shift from the original carrier pump lights.

Keywords: metro/core optical fiber network, optical comb, optical all-wavelength conversion

Classification: Fiber-Optic Transmission for Communications

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1 Introduction

Global data traffic has been steadily increasing because of the rapid development of AI-controlled connecting cars, unmanned aerial vehicles, and IoT devices, as well as the sustainable growth of conventional internet and datacenter traffic. To sustain this, several features, such as large capacity, high efficiency, high speed, and low latency are required for optical fiber networks. These are achieved through metro and core networks that utilize optical paths for wavelength division multiplexing signal transfer with add, drop, and through functions. A reconfigurable add/drop multiplexer (ROADM) works to achieve such flexible optical path networks, and also adds functionalities such as colorless, directionless, contentionless, and gridless operation [1, 2]. However, unusable wavelength channels occur because of frequent add/drop operations, decreasing the utilization efficiency of the network. This problem is called fragmentation. To solve this technical issue, wavelength defragmentation technology has been proposed and investigated. For example, continuous wavelength conversion between transmission and reception [3], hitless defragmentation using the maximum ratio combining wavelength diversity [4], wavelength conversion using single-side-band shifter by using a Mach–Zehnder interferometer-type modulator [5], and reconfigurable channel slicing and stitching with a periodically poled LiNbO$_3$ (PPLN) using a 20 GHz spacing optical comb [6] have been reported. On the other hand, in our group, all-optical wavelength conversion using four-wave mixing (FWM) in highly nonlinear fibers (HNLF) and two-stage LiNbO$_3$ phase modulator (LN-PM)-generated pump light has been experimentally investigated. All-optical wavelength conversion can eliminate the optical-to-electrical and electrical-to-optical conversion between the transmitter and receiver. In addition, using a two-stage optical comb, a high-precision wavelength setup with a wavelength resolution less than that of an optical spectrum analyzer (OSA) could be achieved.
However, the wavelength range is limited because the modulation index for LN-PMs is not sufficient for the pump light extracted from one light source [7].

In this paper, the operating principle of the proposed scheme is explained in Section 2. Next, Section 3 details the experiment performed to extend the wavelength conversion range, where three pump light generation schemes were investigated, and the performance of the generated pump lights were compared. Then, wavelength conversion experiments with the three-stage pump generation, which was found to be the best among the three schemes, and the performance evaluation in terms of bit error rate (BER) are described in Section 4. Finally, we conclude the paper in Section 5.

2 Operating principle

First, experimental setup is explained briefly. A frequency-stabilized seed light is emitted from a laser diode to set the carrier frequency, and an optical comb is generated using LiNbO$_3$ phase modulators (LN-PMs). Then, the target comb mode is extracted as the pump light using an optical band-pass filter. Finally, degenerate four-wave mixing (DFWM) between the pump light and the original signal is performed, and the wavelength is converted. To improve the frequency utilization efficiency in the metro and core networks, a wavelength converted light called idler light is set with a frequency setup precision of less than 1 GHz. The frequency setup precision of the pump light should also be less than 1 GHz because the frequency of the idler light is symmetrical with respect to the signal centered on the pump. Based on this principle, the wavelength of a pump light can be selected flexibly and can be set with high precision using an optical comb. Thus, an idler light can also be set flexibly and precisely.

3 Comparison of pump light generation methods

In a previous report, the selection range of the pump light wavelength was limited to 30 GHz [7]. To expand the wavelength selection range of the pump light, we compared three pump light generation methods. The setup of the first method is shown in Fig. 1(a). A two-wavelength light source is used instead of a one-wavelength light source, and the frequency spacing between two carriers is set at around 50 GHz (precisely 51.75GHz at final condition). The wavelength was 1550.72 nm and 1551.134 nm, and the power was +9 dBm. Sinusoidal RF signals with amplitudes of 1.25 $V_\pi$ and 0.96 $V_\pi$ at a frequency of 10 GHz were used for the 1st and 2nd-stage LN-PM, respectively. $V_\pi$ is the voltage for the $\pi$-phase shift at the 1 GHz drive in the LN-PM. The setup of the second method is indicated in Fig. 1(b). The wavelength of the seed light was 1549.5 nm, and output power was +6.3 dBm. A sinusoidal RF signal with an amplitude of 0.66 $V_\pi$ at a frequency of 40 GHz was used for the 1st-stage LN-PM, while a signal with an amplitude of 1.25 $V_\pi$ at a frequency of 10 GHz was used for the 2nd-stage LN-PM. The setup of the third method is shown in Fig. 1(c). A LN-PM is added, and an optical comb is generated by three-stage LN-PMs. The wavelength of the seed light was 1549.96 nm, and output power was +6.3 dBm. Sinusoidal RF signals with amplitudes of
1.59 \text{ V}, 2.40 \text{ V}, and 2.18 \text{ V}, at a frequency of 10 GHz were used for the 1\textsuperscript{st}, 2\textsuperscript{nd}, and 3\textsuperscript{rd}-stage LN-PM, respectively.

Figs. 1(d), (e), and (f) indicate optical spectra before EDFA3 in each method. In the first method, ten modes with 10 GHz frequency spacing were generated. However, the power of the modes was not stabilized because of the phase difference between the two carriers. In the second method, eleven modes with 10 GHz frequency spacing were generated, but the power of the 2 modes indicated by arrows was low and unstable because of insufficient RF signal power. In the third method, thirteen comb modes with power flatness and 10 GHz frequency spacing were generated.

To investigate the noise characteristics of the comb generated pump, we extracted pump lights generated from the third method’s optical comb using a very narrow optical band pass filter. This time, three pump lights, that have the same frequency as the carrier frequency but ±60 GHz shifted from the original carrier, were extracted. The measured optical spectra are shown in Fig. 2(a). The power extinction ratio was more than 30 dB for all pump lights. The wavelength error between the pump light of the carrier frequency and the pump lights shifted by 60 GHz was less than 0.01 nm, which is the wavelength resolution of the OSA. The pump lights were converted into an electrical signal with a photodetector, and the noise level was measured using an electronic spectrum analyzer. Figs. 2(b) and (c) indicate a comparison between the seed light source and the pump lights. The noise level is considered low enough for a wavelength conversion operation. Further improvement of noise characteristics would be possible by using fiber-laser based optical comb with frequency stabilizing mechanisms [8, 9], but the schemes we investigated were simple configurations as well as low noise.

Fig. 1. Three methods for pump light generation: experimental set ups for (a) first, (b) second, and (c) third method, and optical spectrum before EDFA3 for (d) first, (e) second, and (f) third method.
4 Wavelength conversion experiment with pump light from 3-stage LN-PM optical comb

We performed a wavelength conversion experiment with the pump light generated from the 3-stage LN-PM optical comb. The experimental setup is shown in Fig. 3(a). The original signal was 10 GBaud Return-to-Zero Quadrature Phase Shift Keying (RZ-QPSK) with PRBS with a word length of $2^7 - 1$. The original signal and the pump light were combined with a 3-dB coupler, and they were amplified using a high-power EDFA (HP-EDFA). After that, by transmitting through a 600 m-HNLF, an idler light was generated with DFWM. The idler light was extracted with a BPF and amplified with an EDFA. The wavelength of the original signal was 1549.0 nm, and the average power was 0.5 dBm. The power of each generated pump was $1$ dBm. The power after combination was $-1$ dBm, and $+11$ dBm after the BPF with a bandwidth of 5 nm. The power of the idler light was $-20$ dBm.

The optical spectrum after HNLF is indicated in Fig. 3(b). The wavelength deviation between the original signal, the pump light, and the idler light was less than the wavelength resolution of the OSA. All eye patterns of the idler lights were opened, and the BER measurement results are shown in Fig. 3(c). BER $< 1.0 \times 10^{-10}$ was achieved in all experiments, although there is room for improvement with the reception sensitivity, optimal BPF passband setting, etc. In addition, a power penalty between the original signal and idler light of 3–5 dB at approximately BER $= 1.0 \times 10^{-8}$ was obtained.
5 Conclusion

In this study, we investigated all-optical wavelength conversions using pump light generated from an optical comb, in order to solve the decrease in frequency utilization efficiency caused by wavelength fragmentation.

Three methods of pump light generation were investigated experimentally, and the three-stage LN-PM method generated the most broadband optical combs among the three methods. The pump lights were converted into electrical signals using a photodetector, and the noise level was low enough for the wavelength conversion experiment.

Next, we performed a wavelength experiment, where the idler lights were converted precisely. In addition, a BER of less than $1 \times 10^{-10}$ with a power penalty of 3–5 dB at approximately $BER = 1.0 \times 10^{-8}$.

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