Demonstration of Packet-by-Packet Wavelength Conversion from FP-LD Light to ITU-T Grid Wavelengths

R. Sato, *Member, IEEE*, T. Ito, K. Magari, *Member, IEEE*, A. Okada, M. Oguma, Y. Suzaki, A. Himeno, and N. Ishihara, *Member, IEEE*

***Abstract*—We demonstrated packet-by-packet wavelength conversion from Fabry–Perot laser diode (FP-LD) light to four ITU-T grid wavelengths. To achieve this we used a cross-phase modulation (XPM) wavelength converter and an arrayed-waveguide grating (AWG) router. Good feasibility was obtained at 2.5-Gb/s modulation. Selective wavelength conversion as described here is indispensable for the all-optical networks of future, in which optical signal sources without wavelength control will be used at user-end terminals.**

***Index Terms*—DWDM networks, Fabry–Perot laser diode, ITU-T grid wavelengths, packet-by-packet, wavelength conversion, without wavelength control.**

I. Introduction

Dense wavelength-division-multiplexing (DWDM) photonic technology is currently of great interest as a way to increase the capacity, flexibility, and scalability of all optical networks. Fig. 1 shows an example of an optical network in which each user transmits and receives optical packets via a DWDM-based network. From the viewpoint of the reduction of network costs, a signal source which does not require wavelength control, such as a Fabry–Perot laser diode (FP-LD) or an uncooled distributed-feedback laser diode (DFB-LD) is attractive as an optical transmitter at user-end terminals. To utilize such devices in DWDM systems, however, imprecise wavelengths must be selectively converted to exact DWDM-channel wavelengths at network nodes.

In this letter, we demonstrate packet-by-packet wavelength conversion from imprecise wavelengths to four ITU-T grid wavelengths, by using a cross-phase modulation (XPM) wavelength converter and an arrayed-waveguide grating (AWG) router. We used an FP-LD here as an example of a signal source with wavelengths that are not precisely controlled. We obtained a clear eye-opening at 2.5 Gb/s and confirmed no signal degradation in the back-to-back wavelength conversion, and successfully transmitted converted packets 80 km without using an optical fiber amplifier. We also confirmed 500-m transmission of input FP-LD packets with a power penalty of less than 1 dB.

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R. Sato, T. Ito, K. Magari, A. Okada, Y. Suzaki, and N. Ishihara are with NTT Photonics Laboratories, Atsugi, Kanagawa 243-0198, Japan (e-mail: rieko@aecl.ntt.co.jp).

M. Oguma and A. Himeno are with NTT Photonics Laboratories Naka-gun, Ibaraki 319-1193, Japan.

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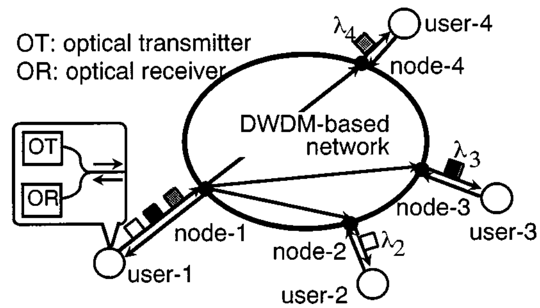

Fig. 1. Example of a DWDM-based network.

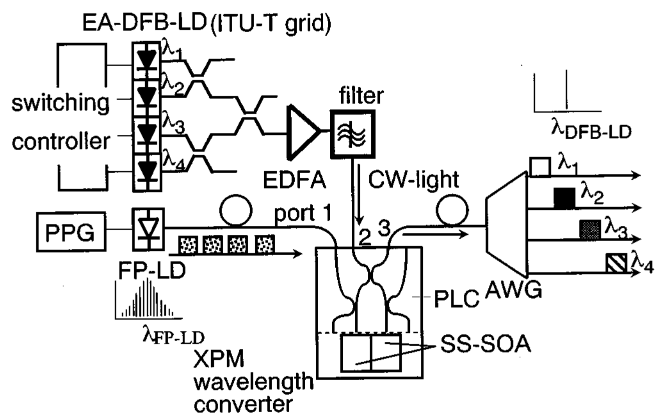

Fig. 2. Experimental setup for selective wavelength conversion.

II. Selective Wavelength Conversion

Fig. 2 shows the experimental setup we used for selective wavelength conversion. Optical packets at 2.5 Gb/s were input to port 1, and continuous-wave (CW) light at an ITU-T grid wavelength was input to port 2. The wavelength of the FP-LD packets was converted to the ITU-T grid wavelengths, and the converted packets were output via port 3 through a single fiber. The output packets were sent to an AWG and then routed to the AWG output ports according to their wavelengths. The AWG mainly acts as a wavelength router in the type of a full-mesh network described in [1]. The AWG also acted as a filter and eliminated input signal light of the FP-LD and the amplified spontaneous emission (ASE) of the semiconductor optical amplifiers (SOAs) in the wavelength converter. The insertion loss of the AWG was 4.5 dB.

The key device here is the wavelength converter. XPM wavelength converters have many attractive characteristics, such as a low degree of chirp during transmission [2], [3]. We employed a hybrid integrated XPM wavelength-converter module [4]. The module consists of a Michelson interferometer with a two-channel spot-size converter integrated semiconductor optical amplifier (SS-SOA) on a planar lightwave circuit (PLC) platform. The spot-size converter is butt-joined to the 1.55-μm bulk active region of the SOA [5]. The SS-SOA is 500 μm long and its front facet is treated with an antireflection (AR) coating. The PLC chip is 15×3 mm^2 and is directly attached to a fiber array by using UV-curable adhesive. The total loss from input port 2 to the SS-SOA, including the coupling loss between the PLC waveguide and the SS-SOA, was estimated as about 11 dB.

The operating principle of the converter is that signal light from an FP-LD is injected into one side of the SS-SOA, and this causes the refractive index of the SOA to change. The change of the refractive index in the SOA determines the interferometric output of CW light at an ITU-T grid wavelength [4]. Although the signal light used here is oscillating in multiple modes, the refractive index is controlled by the optical power level input to the SOA.

The FP-LD is directly modulated at 2.5 Gb/s by a pulse-pattern generator (PPG). We used an optical packet length of 60 bytes with a guard time of 12.8 ns (4 bytes), and the payload patterns were pseudorandom bit sequence (PRBS) $2^{31} - 1$. The average input power at port 1 was 0.7 dBm and polarization control was not used. The bias currents of the SS-SOAs were 55.0 and 80.7 mA. Under these conditions, the wavelength converter operates in a noninverted mode. The bias currents were not adjusted for the four different CW lights that were input. CW light sources of $\lambda 1, \lambda 2, \lambda 3, \lambda 4$, (1552.6, 1553.4, 1554.2, and 1555.0 nm) (100-GHz spacing) were selected by switching four modules, each containing an electroabsorption modulator integrated with a DFB-LD (EA-DFB-LD). The wavelengths we used here had central frequency deviations within the ± 10 GHz range stated in the ITU-T recommendation. We used a fiber amplifier to increase the CW power.

In this experiment, the residual modes of the FP-LD after filtering may have caused crosstalk problems. Therefore, we set the peak wavelength of the FP-LD well away from the 1.55-μm wavelengths of the EA-DFB-LDs.

In the bit-error-rate (BER) measurement, we did not use a burst-mode receiver but a DC-coupled APD receiver. A PPG, error-detector, and switching controller of EA-DFB-LDs were all synchronized together. To measure the BER characteristics at PRBS $2^{31} - 1$, we converted the wavelengths of all the packets to λ_2.

III. Experimental Results

Fig. 3(a) and (b) shows the spectra of the input light of the FP-LD and an example of the converted output light at AWG output port 2. Oscillations in multiple modes were converted to oscillation in a single mode. We confirmed that the neighboring residual mode of the FP-LD was suppressed to less than -13 dB at all AWG output ports. Fig. 4(a) shows the 2.5-Gb/s optical packets generated by the FP-LD. Fig. 4(b) shows the converted output packets at each AWG output port. We successfully

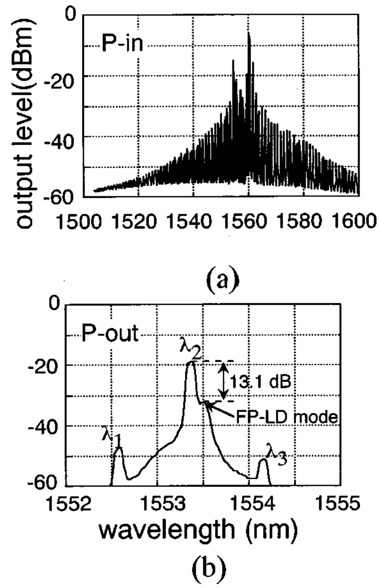

Fig. 3. Input and output light spectra. (a) Input light (FP-LD). (b) Example of converted output light (DFB-LD).

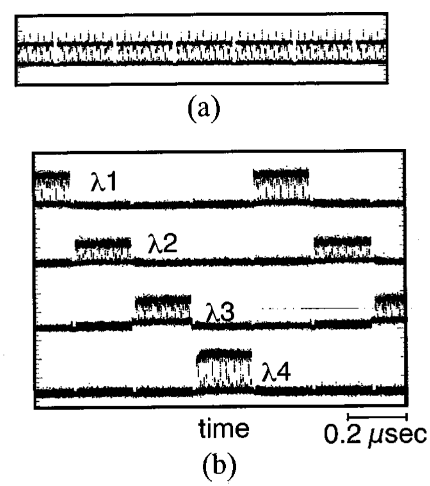

Fig. 4. Input and converted output packets. (a) Input optical packets generated by the FP-LD. (b) Converted output packets at each AWG port.

achieved the packet-by-packet conversion from the wavelengths of the FP-LD to four ITU-T grid wavelengths. The output power levels and extinction ratios differ among the four wavelengths in Fig. 4(b). This is because of the polarization dependence of the input CW-light (not the signal light), which has different input polarization for four different light sources.

Fig. 5 shows the BER curves for the back-to-back condition and for the transmission experiments. The crosses show the BER curves for the input FP-LD packets without wavelength conversion. The white circles show the BER curves for the converted output packets at a wavelength of λ_2 (back-to-back). The inset eye-patterns are produced by the converted output packets. A clear eye-opening and no power penalty were observed in the back-to-back condition. Furthermore, the BER curves of converted output packets transmitted 80 km along single-mode fiber (SMF) after back-to-back wavelength conversion are also shown (white squares in Fig. 5). No optical fiber amplifier was

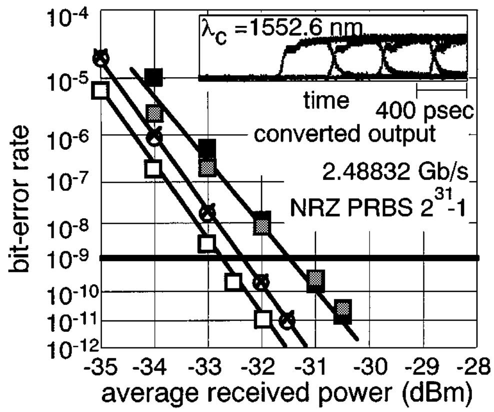

Fig. 5. BER curves and eye patterns. Crosses: Input FP-LD packets without wavelength conversion. White circles: Converted output packets (back-to-back, $\lambda_c = 1552.5$ nm). Black squares: Input FP-LD packets with 500-m transmission through SMF. Gray squares: Converted output packets with 500-m transmission through SMF before wavelength conversion ($\lambda_c = 1552.5$ nm). White squares: Converted output packets with 80-km transmission through SMF after wavelength conversion ($\lambda_c = 1552.5$ nm).

used in the transmission span, and a slight improvement of sensitivity was observed. We assume this to be the dispersion compensated effect that occurs when a signal in a noninverting mode is transmitted through SMF [4].

Experimental results for transmission of input FP-LD packets along SMF are also shown in Fig. 5. The black squares show the BER curves of FP-LD packets after a 500-m transmission. It is clear that the signal was degraded because of the wide-band spectrum of the FP-LD. A 500-m transmission distance is possible at a power penalty of less than 1 dB with a BER of 10^{-9}. When we take the transmission distance of the FP-LD packets into consideration, systems to which the FP-LD signal source would be applicable are, for example, local area networks in buildings in which the transmission distance between each user and a wavelength converter at a node is less than 500 m. We confirmed that there was no power penalty for the output packets at a wavelength of λ_2 converted from FP-LD packets after a 500-m transmission (gray squares in Fig. 5).

These experimental results—no signal degradation caused by the wavelength conversion and successful 80-km transmission after wavelength conversion along SMF without an optical amplifier—show the feasibility of this technique for use in DWDM networks.

From these results, signal sources with a wavelength that is not precisely controlled (not only FP-LDs but also uncooled DFB-LDs) are applicable to DWDM-based optical networks when selective wavelength conversion is used to create exact DWDM-channel wavelengths.

IV. Conclusion

We successfully demonstrated the packet-by-packet wavelength conversion of 2.5-Gb/s optical signals from FP-LD light to four ITU-T grid wavelengths by using an XPM wavelength converter and an AWG router. Selective wavelength conversion using signal sources that do not require wavelength control is a candidate technology for designing the optical networks of future.

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