# Multichannel Bidirectional Transmission Using a WDM MUX/DMUX Pair and Unidirectional In-Line Amplifiers

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***Abstract*— We propose a repeated bidirectional WDM transmission system using cascaded WDM MUX/DMUX pairs as narrow-bandpass filters and reflection attenuators. Fiber span is increased by inserting unidirectional EDFA's between WDM MUX/DMUX pair as in-line amplifiers. A three-channel hybrid system with one 10-Gb/s and two 2.5-Gb/s channels is also demonstrated in the 1550-nm region for transmission over 150 km of dispersion-shifted fiber. Negligible power penalty due to back reflection was observed.**

***Index Terms*— Bidirectional transmission, four-wave mixing, optical fiber amplifier, wavelength-division multiplexing.**

## I. Introduction

WAVELENGTH-division-multiplexing (WDM) is essential for realizing high-capacity lightwave transmission and flexible optical networks [1]–[2]. Compared with unidirectional transmission, bidirectional transmission over a single fiber reduces the required number of fibers. The feasibility of bidirectional optical amplification has been reported recently [3]–[6]. Previous schemes include the use of bidirectional erbium-doped fiber amplifiers (EDFA's) without isolators [3]; optical circulators with separate amplification of the signals [4]; 3-dB couplers to separate the signals before and after amplification [5]; subsidiary erbium-doped fiber in an EDFA [6]; and repeaterless bidirectional transmission [7]–[8]. One important problem in bidirectional transmission is that the system degrades seriously by back reflections from processes such as stimulated Brillouin scattering (SBS) [9] and Rayleigh backscattering. In this letter, we propose an in-line amplified bidirectional WDM transmission system using cascaded WDM multiplexer/demultiplexer (MUX/DMUX) pairs as narrow bandpass filters and reflection attenuators. An eight-wavelength system is shown, for example, in Fig. 1. Each WDM channel can transmit signals in either direction. Unidirectional EDFA's were inserted between WDM MUX/DMUX pairs as in-line amplifiers to increase the fiber span. To reduce cost, one pump laser may be shared by several EDFA's [10]. Adjacent channel spacing is doubled by selecting the odd-channel signals in the forward direction and the even-channel signals in the opposite direction. The channel assignment could, for example, be based on the ITU proposal of 200-GHz (1.6-nm) spacing. Identical WDM MUX/DMUX pairs may be employed in both ends of the fiber link to launch or receive each optical channel.

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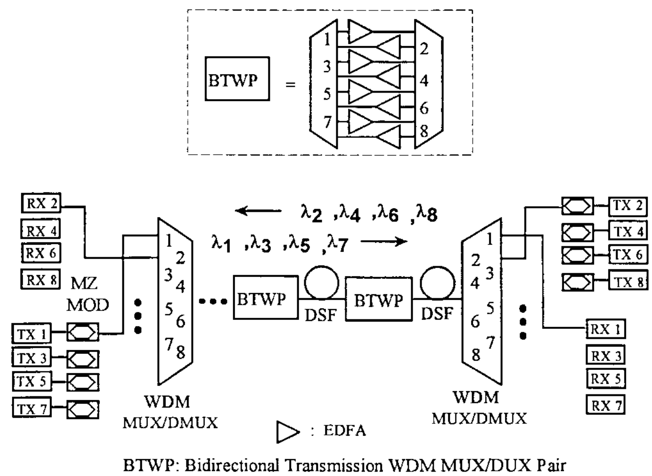


Fig. 1. A proposed multichannel in-line amplified bidirectional transmission system using a cascaded WDM MUX/DMUX pair. MZ MOD: Ti:$LiNbO_3$ Mach–Zehnder external modulators; DSF: dispersion-shifted fiber.

## II. System Configuration

The experimental setup in Fig. 2 is used to demonstrate a three-channel bidirectional WDM transmission system, based on the general idea shown in Fig. 1. A hybrid 10- and 2.5-Gb/s WDM bidirectional transmission system is constructed using a WDM MUX/DMUX pair-based in-line amplifier. There are three DFB lasers with wavelengths of 1552.8-nm $(\lambda_3)$ at the left-hand side (forward direction), and 1551.1-nm $(\lambda_2)$, and 1554.3-nm $(\lambda_4)$ at the right-hand side (backward direction). Both $\lambda_2$ and $\lambda_4$ are adjacent channels (Chs. 2 and 4) to $\lambda_3$ (Ch. 3) in the MUX/DMUX pair with an adjacent channel spacing of 200 GHz. The 10- and 2.5-Gb/s PRBS $2^{23}-1$ NRZ electrical signals are used to modulate the Ti:$LiNbO_3$

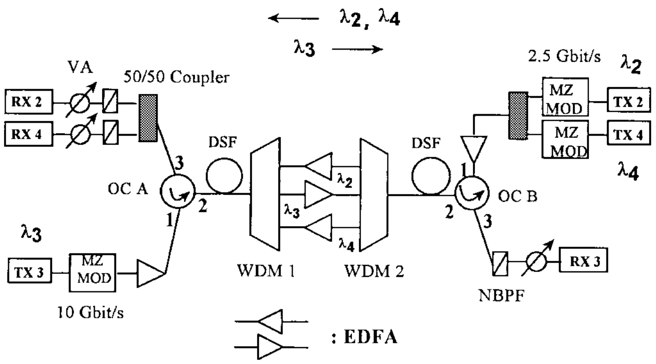


Fig. 2. Experimental setup for a three-channel bidirectional WDM transmission. VA: variable optical attenuator; NBPF: narrow-bandpass filter; OCA/OCB: optical circulators A/B.

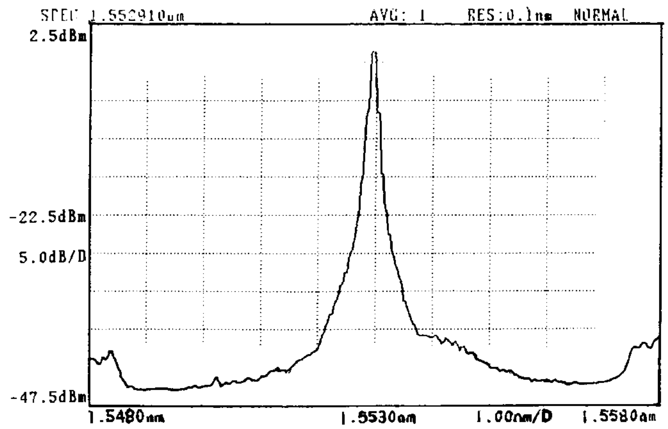


Fig. 3. Optical spectrum of the forward-transmission after WDM2.

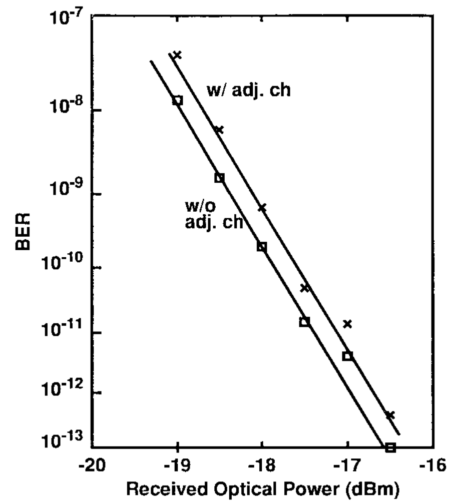


Fig. 4. BER curves of the 10-Gb/s signal $\lambda_3$ as a function of received optical power with unidirectional and bidirectional transmission.

Mach–Zehnder (MZ) external modulators for the forward and the backward directions, respectively. In this experiment, instead of using a WDM MUX/DMUX pair at both ends, two polarization-independent three-port optical circulators are used to launch the amplified signals from port 1 into the fiber link and to receive the signals coming from ports 2 to 3. The optical signals are transmitted through 2 $\times$ 75 km of dispersion-shifted fiber (DSF). The DSF's used in the experiment have $D = 2.7$ ps/km·nm and zero dispersion wavelengths $(\lambda_o)$ ranging from 1557.0 to 1566.2 nm. The average attenuation of these dispersion-shifted fibers were about 0.3 dB/km. Beside ports 3–5, the other ports between the MUX/DMUX pair were disconnected. In this bidirectional transmission configuration, high-signal power levels for both directions did not occur at any point along the fiber link (i.e., small products of optical power). Also, the phase matching condition could not easily happen between these opposite propagating signals. Thus, four-wavelength mixing (FWM) was not observed in this experiment. The WDM MUX/DMUX pair, based on a multilayer interference filter, have the characteristics of 200-Ghz channel spacing, full-width at half-maximum (FWHM) bandwidth of 0.6 nm, and insertion loss of about 3.0 dB. Also, the minimum isolation between channels is $>$30 dB and the back reflection effect is less than $-$45 dB. The MUX/DMUX pair functions as a narrow-bandpass filter to select the desired signal, reject the amplifier noise and block the reflected signals from the opposite direction. All the connectors used here have return loss $< -45$ dB. The signal at $\lambda_3$ is amplified by an EDFA located between the third channel of the MUX/DMUX pair, while the reflected signals $\lambda_2$ and $\lambda_4$ are blocked twice by the MUX/DMUX pair. Instead of using a DMUX, a 0.6-nm narrow-bandpass filter, connected to port 3 of optical circulator B, is used to filter out the backward reflection signals, which is mainly caused by the imperfect isolation of optical circulator B from ports 1 to 3. The 10-Gb/s signal $\lambda_3$ is detected by a high-sensitivity receiver, and the BER is measured. The configuration is symmetrical for the backward direction transmission.

## III. Results and Discussion

At the common port of WDM1, the signal levels are $-11.0$ dBm for $\lambda_3$ in the forward direction, and $+9.0$ and $+9.5$ for $\lambda_2$ and $\lambda_4$ in the backward direction, respectively. The noise figure (NF) of the bidirectional transmission WDM MUX/DMUX pair (BTWP) is about 3.3-dB higher than that of those EDFA's ($\sim$4.0 dB in the 1550-nm band @ $P_{\rm in} = -10$ dBm) inside the BTWP. The measured NF at $\lambda_2$, $\lambda_3$, and $\lambda_4$ were 7.4, 7.1, and 7.5 dB, respectively, for the BTWP. It is mainly due to the high-insertion loss characteristic of the WDM DMUX. In the forward direction, the back-reflection of amplified signals $(\lambda_2$ and $\lambda_4)$ are only about 15 dB down and are not negligible when compared with $\lambda_3$. However, using a 90/10 fiber coupler for monitoring, Fig. 3 shows that no crosstalk from $\lambda_2$ and $\lambda_4$ is observed after WDM2. The signal-to-noise ratio (SNR) of $\lambda_3$ is better than 35 dB. Fig. 4 shows the bit-error-rate (BER) performance of $\lambda_3$ as a function of received optical power with/without $\lambda_2$ and $\lambda_4$ as adjacent wavelengths. The result shows that the adjacent count propagating channels of $\lambda_2$ and $\lambda_4$ do not degrade the system performance at $\lambda_3$. Here, we show only the BER performance of the 10-Gb/s signal at $\lambda_3$ because it is located between the two 2.5-Gb/s signals of the counter-propagating direction and is supposed to have the largest crosstalk effect among these three channels. However, negligible system power penalties of less than 0.3 dB and no error floor are observed. The 0.3-dB degradation might be induced from cross-phase modulation or other fiber nonlinearity effects, and this topic is currently under study.

## IV. Summary

We have proposed an eight-channel in-line amplified bidirectional WDM transmission system using cascaded BTWP's as narrow bandpass filters and reflection attenuators. Unlike repeaterless transission, fiber span of this proposed configuration could be increased by locating EDFA's inside the BTWP' as in-line amplifiers. We also have demonstrated a three-channel hybrid bidirectional transmission system in the 1550-nm region over 150 km of DSF. In our experiment, by using the WDM MUX/DMUX pair as narrow-bandpass filters and reflection attenuators, the back reflection effects were negligible since the BER degradation of the central channel (10 Gb/s) is less than 0.3 dB for the bidirectional transmission when compared with single-channel, unidirectional transmission.

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