Penalty-free 100-km Transmission of 53-Gbps/λ IM-DD Signal Enabled by a Novel Zero-dispersion Wavelength Estimation and Optimization Method

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***Abstract*— A novel zero-dispersion wavelength estimation and optimization method for detecting unique spectral notches caused by chromatic dispersion was proposed and experimentally demonstrated to be feasible, achieving a penalty-free transmission of 53.125 Gbps/λ over 100 km.**

Keywords—IM-DD, chromatic dispersion, zero-dispersion wavelength, data center interconnection

I. INTRODUCTION

The massive deployment of broadband services has led to the creation of new application services in recent years, such as those used for autonomous driving, telemedicine, and cyber physical systems. To provide these application services, the demand for high-speed transmission systems is increasing in data center interconnections (DCI). In particular, as an example of high-speed transmission systems in DCI, hyperscale DC networks have been studied to further scale expansion by connecting geographically distributed DCs. In Reference [1], multiple data centers are connected to each other and to a duplexed Regional Network Gateways (RNGs) to enable intercommunication. The distance between data centers and RNGs is typically less than 100 km. Among the methods to achieve high-speed transmission systems with transmission distances less than 100 km, intensity modulation and direct detection (IM-DD) is being actively studied because it has lower cost and lower power consumption than coherent detection [2-4]. A major topic in high-speed transmission systems with IM-DD is how to compensate for waveform degradation due to chromatic dispersion. Many solutions to this problem have been proposed such as adopting single sideband and vestigial sideband modulation schemes, using advanced N-level pulse amplitude modulation technologies (PAM-4 and -6), and applying digital signal processing such as 3rd-order nonlinear Volterra filters and recurrent neural networks [2–4]. Thus, although there are methods to compensate for chromatic dispersion at the transmitter and receiver sides, there are few methods to reduce chromatic dispersion by obtaining (or estimating) the zero-dispersion wavelength (ZDW) of an optical fiber and tuning the emission wavelength to the ZDW.

As is well known, chromatic dispersion is generated by the product of the dispersion parameter D in an optical fiber and transmission distance L, and D increases in accordance with the deviation of the laser-emission wavelength λ from the ZDW of an optical fiber. However, the typical ZDW of a single mode fiber (SMF) adopted in access networks is specified in the range of 1300-1324 nm in ITU-T G.652 and varies due to the effects of waveguide dispersion and material dispersion. Based on this, the transmission distance of high-speed IM-DD is limited because optical transceivers must be designed on the basis of the worst possible variance value that can be taken for the ZDW variation.

In this paper, we propose a novel ZDW estimation and optimization method for high-speed IM-DD transmission. This method can reduce chromatic dispersion by optimizing the emission wavelength to the estimated ZDW with a wavelength-tunable (or selective) laser. We verified the feasibility of this method and achieved a penalty-free

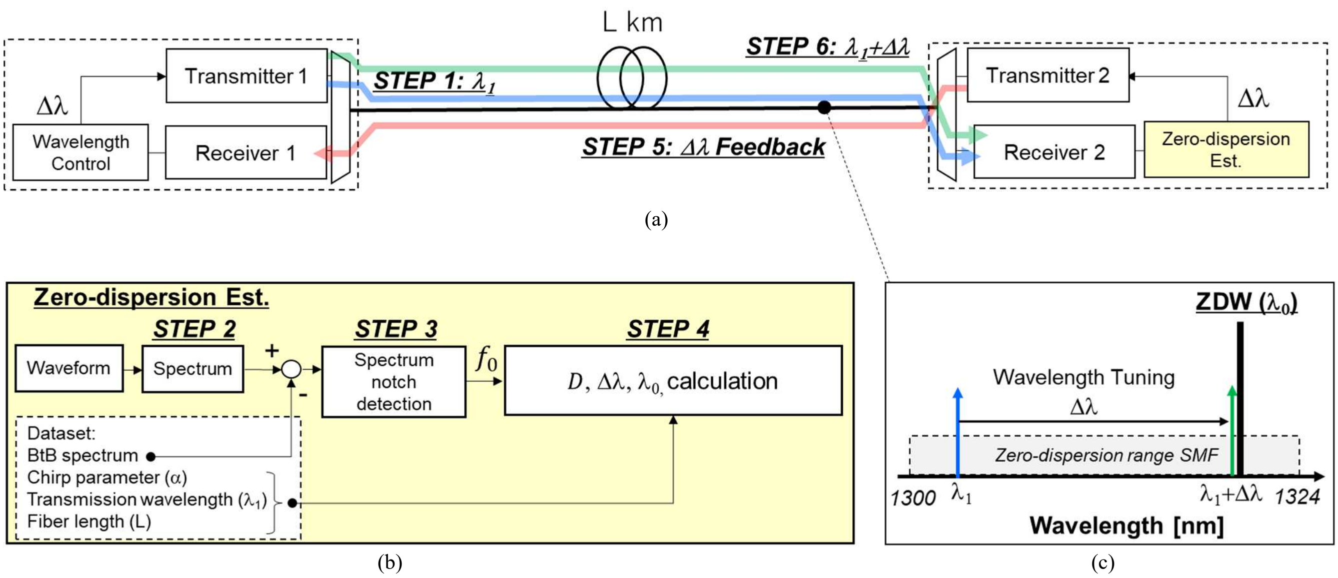


Fig. 1. Proposed method; (a) System configuration, (b) ZDW estimation block, and (c) relationship wavelength.

transmission of a 53.125 Gbps/λ over 100 km without dispersion compensation.

II. ZERO-DISPERSION WAVELENGTH ESTIMATION METHOD

Fig. 1 shows the proposed method to estimate the ZDW. The procedure consists of six steps.

Step 1: The client signal is output from transmitter 1 at a wavelength λ_1 and received in receiver 2 via the SMF.

Step 2: The received signal is input into the "zero-dispersion estimation" block, the waveform in the time domain is obtained from the received signal, and a frequency spectrum (FS) is extracted by executing the fast Fourier transformation (FFT) as shown in Fig. 1 (b).

Step 3: The unique notch spectrum is obtained by the division of the FS after transmission and the back-to-back (BtB) FS that is held as a dataset and detects the minimum value f_0 outside of integer multiples of the signal in the power spectral density. As shown by Devaux et al. [5], the f_0 is the notch frequency related to the dispersion parameter D as in (1).

Step 4: By using the chirp parameter α of transmitter 1, wavelength λ_1, fiber length L, f_0 of the notch frequency, and speed of light c, D is found from equation (1) in Devaux et al. [5]. By dividing D obtained in (1) by the general dispersion slope value 0.092, the ZDW shift $\Delta\lambda$ is calculated as in (2) and ZDW λ_0 is calculated as in (3).

$$DL = \frac{c}{2f_0^2\lambda_1^2}\left(1 - \frac{2}{\pi}\arctan\alpha\right) \qquad (1)$$

$$\Delta\lambda = D/0.092 \qquad (2)$$

$$\lambda_0 = \lambda_1 + \Delta\lambda \qquad (3)$$

Step 5: Transmitter 2 sends the obtained $\Delta\lambda$ information to receiver 1 as a control signal (see Fig. 1 (a)).

Step 6: The emission wavelength in transmitter 1 is adjusted from λ_1 to $\lambda_0 = \lambda_1 + \Delta\lambda$ on the basis of the received control signal.

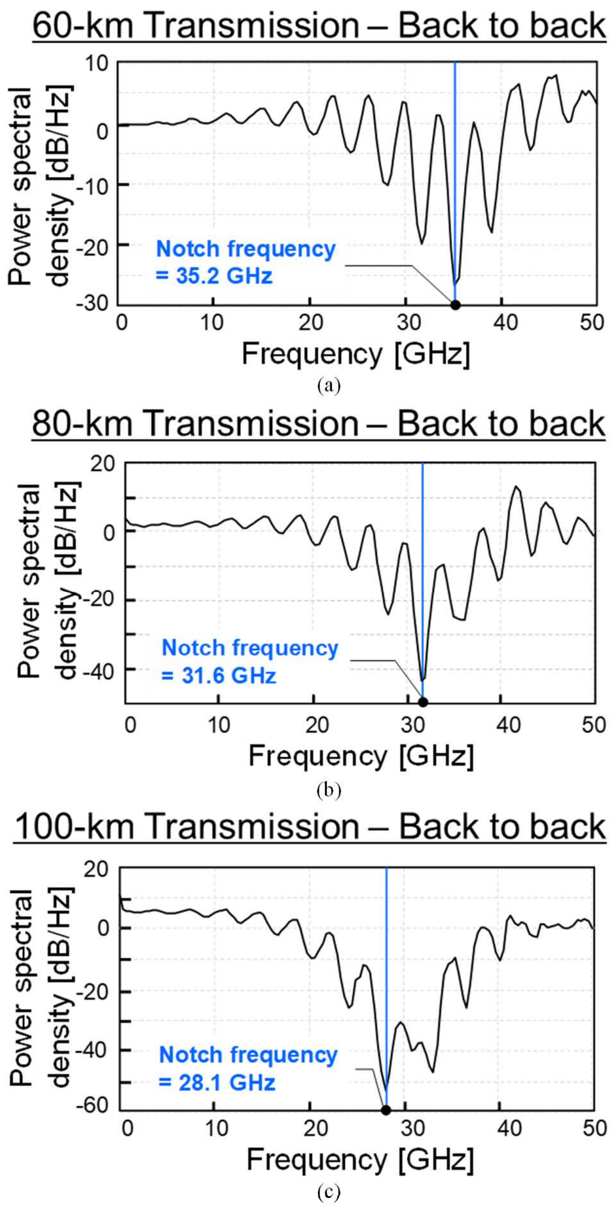
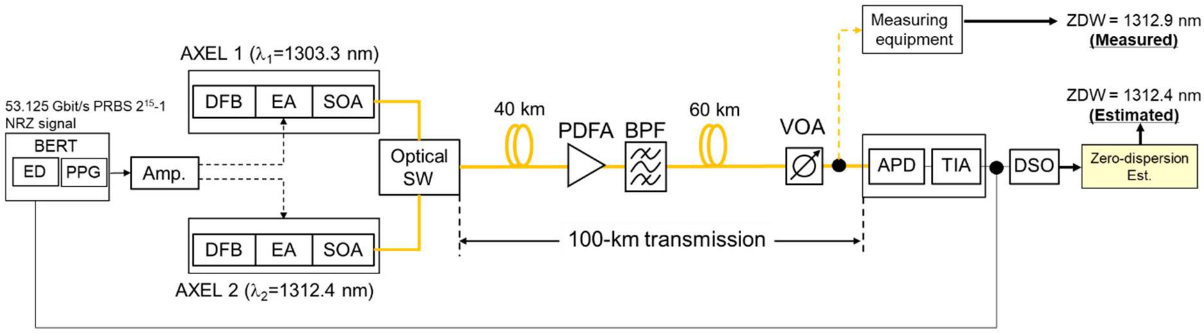


Fig. 2. Spectra extracted from the division between transmission and BtB: (a) 60-km, (b) 80-km, and (c) 100-km transmission.

TABLE I. NOTCH FREQUENCY f_0, ZDW λ_0 (ESTIMATION, AND TRUE VALUE), AND ESTIMATION ERROR.

	Experiment (estimation)		True value	Estimation error
Fiber Length (km)	f_0 (GHz)	λ_0 (nm)	λ_0 (nm)	$\delta\lambda$ (nm)
60	35.2 →	1313.0	1313.2	0.2
80	31.6 →	1312.3	1313.2	0.9
100	28.1 →	1312.4	1312.9	0.5



BERT: Bidirectional Encoder Representations from Transformers. PPG: Pulse pattern generator.
ED: Error detector. Amp.: Amplifier. EA: Electro-absorption modulator.
SOA: Semiconductor optical amplifier. PDFA: Praseodymium doped fiber amplifier. BPF: Band pass filter.
VOA: Variable optical attenuator. APD: Avalanche photodiode. TIA: Transimpedance amplifier. DSO: Digital storage oscilloscope.

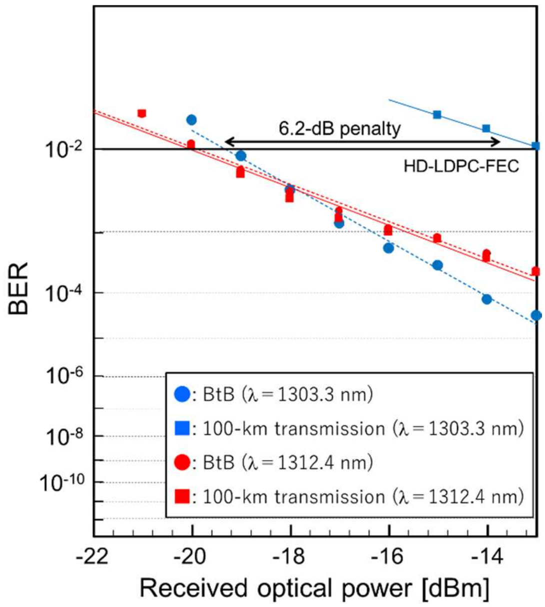
Fig. 3. Experimental setup.

This method can estimate the ZDW of the SMF by simple calculation from D and can reduce the chromatic dispersion penalty by tuning the emission wavelength. Fig. 1 (c) illustrates the summary in this method. The ZDW of the SMF in the transmission line is estimated, and the chromatic dispersion penalty is reduced by tuning the emission wavelength to the ZDW in accordance with the estimation value in one.

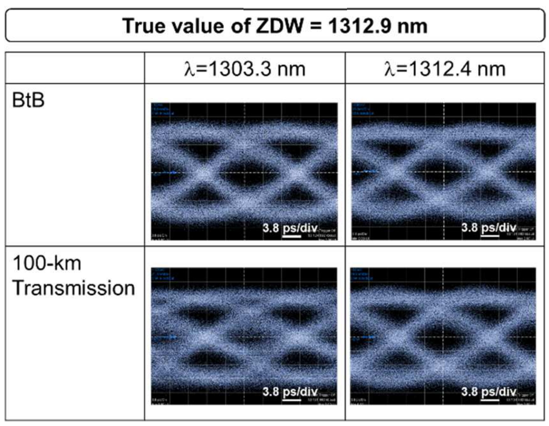
Fig. 2 shows the FS of the proposed method obtained by dividing the FS after SMF transmission and the BtB FS. The transmitter was a semiconductor optical amplifier (SOA) integrated electro-absorption modulated distributed-feedback (EA-DFB) laser (AXEL) with $\lambda = 1303.3$ nm and $\alpha = 0.41$ [6]. Pseudorandom binary sequence (PRBS) 2^{15}-1 non-return-to-zero (NRZ) signals at 53.125 Gbps were transmitted for a total of 60, 80, and 100 km. Waveforms of the received signals were acquired by using a digital storage oscilloscope at 200 GS/s, and frequency spectra were created with an FFT size of 512. The notch frequencies f_0 of 60-, 80-, and 100-km transmission were 35.2, 31.6, and 28.1 GHz, respectively. As shown in equation (1), we experimentally confirmed that the notch frequencies in Fig. 2 (a), (b), and (c) appear in different positions depending on the transmission distance. Table I shows the ZDW estimated from f_0, the true value of the ZDW obtained from the dispersion measurement, and the estimation error. Since each estimation error is sufficiently small relative to the true value, these results show that the ZDW of the SMF can be estimated.

III. EXPERIMENT AND RESULTS

Fig. 3 shows the experimental setup to evaluate the penalty reduction with the proposed method. We used two AXELs with fixed wavelengths to adjust the wavelength on the transmitter side since a wavelength-tunable laser was unavailable. Emission wavelengths of the two AXELs were 1303.3 and 1312.4 nm, respectively. The NRZ signal at a bitrate of 53.125 Gbps with PRBS 2^{15}-1 generated from the



(a)



(b)

Fig. 4. Experimental results; (a) BERs and (b) eye diagrams.

pulse pattern generator (PPG) was amplified by an electrical amplifier. Then, the modulation signal was input into the EA in AXELs. The optical signal was amplified by a praseodymium doped fiber amplifier (PDFA), passed through a band pass filter (BPF) to cut off amplified spontaneous emission, and received by the 50 Gbps class avalanche photodiode transimpedance amplifier (APD-TIA) through a total of 100-km SMF [7]. The bit error rate (BER) of the received signal was measured by using an error detector (ED). On the other hand, the equipment to measure the wavelength dispersion was used to evaluate deviations from estimates. The two SMFs used totaled 100 km and had the same ZDW as in Section 2 when they were considered as one pseudo 100-km SMF.

Fig. 4 (a) and (b) show the experimental results of BERs and eye diagrams, respectively. The different BER slopes at λ_1 = 1303.3 nm and λ_2 = 1312.4 nm are due to different device characteristics. In the case of $\lambda_1 =$ 1303.3 nm, which is distant from the ZDW at 9.6 nm, the chromatic dispersion penalty was 6.2 dB with a BER = 1×10^{-2} (HD-LDPC-FEC limit) due to the deviation from the ZDW of the SMF after a transmission distance of 100 km. On the other hand, in the case of λ_2=1312.4 nm, which is slightly distant from the ZDW at 0.5 nm, the chromatic dispersion penalty was negligible after 100-km transmission, and receiver sensitivity of -20 dBm was achieved. The proposed method can estimate the ZDW without using an additional dedicated measurement device and successfully achieved a penalty-free transmission of 53.125 Gbps/λ over 100 km by optimizing the emission wavelength.

IV. Conclusion

We proposed a novel ZDW estimation and optimization method for high-speed IM-DD transmission. An experimental demonstration verified the feasibility of this method, and penalty-free transmission of 53.125 Gbps/λ over 100 km was successfully achieved. The proposed method can relax restriction on the transmission distance in high-speed IM-DD without dispersion compensating technique or equalizer.

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