43-Gbps RZ-DQPSK TRANSPONDER FOR LONG-HAUL OPTICAL TRANSMISSION SYSTEM

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We have successfully developed a high performance transponder subsystem first in the world by using 43-Gbps RZ-DQPSK (Return to Zero Differential Quadrature Phase Shift Keying) modulation formats. We have already manufactured, inspected and shipped over three hundred transponder subsystems as a commercial product of optical transmission system to a domestic major telecommunication career. Our transponder is applicable to high capacity optical networks which are recommended by international standard OTN (Optical Transport Network) and the combination of our transponder and OTN-framer including Forward Error Correction (FEC) realizes a DWDM (Dense Wavelength Division Multiplexing) optical transmission system which operates over 43-Gbps per wavelength channel. This paper reports features, configuration and performance of 43-Gbps RZ-DQPSK Transponder subsystem.

INTRODUCTION

An optical transmission system of more than 40 Gbps needs to be established to succeed the conventional 10-Gbps transmission system. However, if 40-Gbps signals with narrow pulse width for 1 bit and wide frequency bands are transmitted through the existing fiber transmission system, the signals are affected by amplified spontaneous emission (ASE) noises which occur and accumulate at the repeater amplifiers, as well as by chromatic dispersion or polarized mode dispersion at the erbium-doped fiber amplifier (EDFA) or in the fibers. As a result, the transmission reach is more restricted than that of the existing system. Therefore, new modulation/demodulation formats which transmit information by modulating optical phases are being examined, such as Differential Phase Shift Keying (DPSK), Differential Quadrature Phase Shift Keying (DQPSK), and RZ-DQPSK format in which DQPSK codes are RZ (return to zero) modulated to improve receiving characteristics. These offer superior characteristics against noises or distortion of signal waveform owing to chromatic dispersion or polarized mode dispersion, and have the same or more transmission capability than the conventional formats such as the On-Off Keying (OOK) format including the Non Return to Zero (NRZ), which turns on/off optical intensity.

Against such a backdrop, Yokogawa has been developing a long-haul dense wavelength division multiplexing (DWDM) transmission system with 43 Gbps per wavelength, and has created a transponder subsystem (“transponder”) incorporating the 43-Gbps RZ-DQPSK modulation/demodulation format to overcome various technological problems. This paper describes the features, configuration, and performance of this system.

Table 1 Comparison of Characteristics of 43-Gbps Modulation Formats

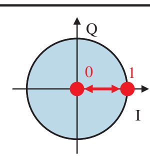
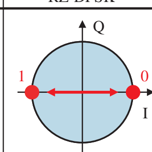
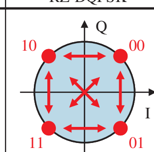
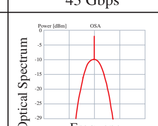
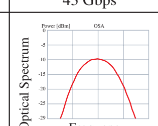
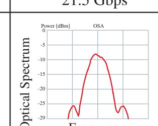
Modulation format	NRZ	RZ-DPSK	RZ-DQPSK
Constellation I: In-Phase Q:Quadrature-Phase			
Symbol Rate	43 Gbps	43 Gbps	21.5 Gbps
Modulated optical spectrum (Simulation)			

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Table 2 Main Characteristics of RZ-DQPSK Format

Characteristics of RZ-DQPSK	Superiority and characteristics
Narrow spectrum width occupied	· Efficient use of frequencies · Secure from waveform distortion and excellent tolerance to chromatic dispersion
2 bits of data are allocated to each of four modulated optical phases	· Modulating or demodulating operations at half the speed of bit rates transmitted or received · Wide pulse width and high tolerance to waveform distortion
Complicated format	· At the transmitting part, a DQPSK encoder with pre-coding function and phase-shift modulation function is needed. · At the receiving part, functions for modulating phase information to intensity information, or converting light to electricity are needed.

CHARACTERISTICS OF RZ-DQPSK MODULATION

Table 1 compares the characteristics among representative formats for 43-Gbps modulation.

RZ-DQPSK modulation is suitable for high-density wavelength multiplexing or long-haul transmission systems because it occupies a narrower spectrum width and has a wider pulse interval for 1 bit compared with RZ-DPSK and On-Off Keying. RZ-DQPSK could also be feasible for high-speed circuits for transmitting and receiving ends respectively. Therefore, this format is superior in viability and stability of high-frequency integrated circuits for operating or amplifying at optical transmitting/receiving parts. Table 2 shows the advantages of the RZ-DQPSK format in terms of the main characteristics.

SCHEMATIC SPECIFICATIONS OF TRANSPONDER

External view and block diagram

Figure 1 shows an external view of the transponders: current model (left) and latest 'Global model' (right), and Figure 2 their block diagram. The dimensions of the 'Global model' transponder are 5 × 7 × 0.7 inch, whereas those of the current model are 320 × 110 × 40 mm, which both consist of the transmitting part, the receiving part, and the external interface part. The 'Global model' transponder is compact and maintains the features of the current model. The following description is mostly about the current model transponder. The transponder has radiation fins for cooling. The design of the fins is optimized based on a heat calculation model for the airflow volume and its direction during operation. The casing material is made of aluminum alloy.

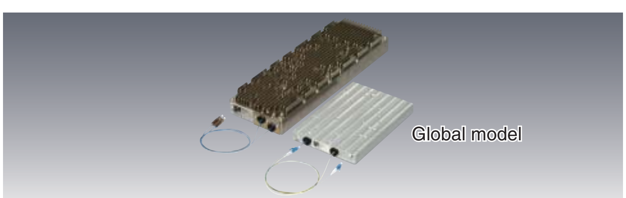

Figure 1 External View of RZ-DQPSK Transponders

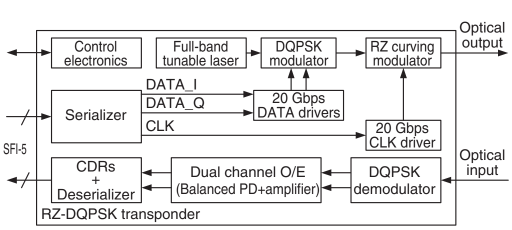

Figure 2 Block Diagram of RZ-DQPSK Transponder

Table 3 Main Specifications of Transponder

Part	No	Description	Specification/performance	Condition/notes
General	1	Operation temperature range	-5°C to +70°C	Casing temperature
	2	Power source voltage	1) +5.0 V 2) +3.30 V 3) -5.20 V	
	3	Main signal electric interface	300 pin MSA*1 compliant	
	4	Operation bit rate	1) 43.0 Gbps 2) 44.6 Gbps	Mark ratio 50%
	5	Dimensions	320 × 110 × 40 mm	
	6	Weight	2.5 kg	
	7	Power consumption	38 W	
Transmitting part	8	Optical output power	-8 dBm	
	9	Wavelength tunable range	1) 1528.77 to 1563.45 nm 2) 1570.42 to 1607.04 nm	50 GHz ITU*2-Grid compliance
	10	Wavelength setting stability	≤ ±20 pm	
	11	RZ modulated extinction ratio	>13 dB	
	12	Optical spectrum width	≤ 0.4 nm	3 dB band
Receiving part	13	Receiving wavelength range	1) 1528.77 to 1563.45 nm 2) 1570.42 to 1607.04 nm	50 GHz ITU*2-Grid compliance
	14	Receiving optical power	+ 4 dBm	
	15	Min. receiving optical sensitivity	- 4 dBm	Bit error rate ≤ 1×10^{-12}
	16	Optical return loss	≥ 30 dB	
	17	Tolerance to chromatic dispersion	≥ ±100 ps/nm	≤ 2 dB Q factor penalty
	18	Tolerance to DGD	≥ 20 ps	≤ 2.5 dB OSNR penalty

*1: Multi Source Agreement(2) *2: International Telecommunication Union

Main specifications of transponder

Table 3 shows the main specifications of the transponder. The transmission rate is set to 44.6 Gbps so that at the client side the transponder can respond not only to 43.0 Gbps for Synchronous Digital Hierarchy (SDH)/Synchronous Optical Network (SONET) but also to 4 × 10 GbE-LANPHY (physical layer standard of Ethernet). The L or C band can be selected as the range of wavelength for both the transmitting part and receiving part.

As for the receiving part, the main characteristic is degradation of bit error rate (BER) whose value can be measured with the optical signal to noise ratio (OSNR) by overlapping ASE noises on input main signals. Other important performance indices are OSNR penalty and Q factor penalty. The OSNR penalty is measured based on parameters which cause waveform distortion, such as chromatic dispersion corresponding to transmission reach through fibers or differential group delay (DGD) which is the difference in diffusion time among mutually perpendicular polarized waves. The Q factor penalty is converted from BER.

Example of incorporation into long-haul DWDM transmission device

Figure 3 shows an example of incorporating the transponder into a long-haul DWDM transmission device.

At the client side, the routes of 39.8-Gbps NRZ optical signals compliant with SDH/SONET are changed by optical cross-connects (OXC) or optical routers and connected to the line cards in the

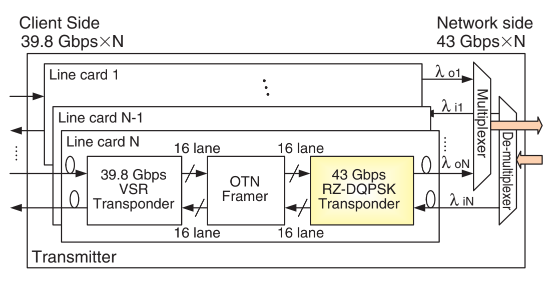

Figure 3 Example of Transmission Device for Long-haul DWDM System

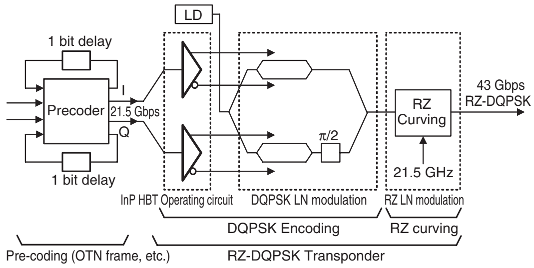

Figure 4 RZ-DQPSK Modulation Coding Part

transponder. At the network side, according to the wavelengths allocated to each line card, 43-Gbps RZ-DQPSK encoded data is multiplexed with wavelength multiplexers or de-multiplexed with wavelength de-multiplexers, and transmitted/received over long distances of several hundred kilometers.

Each line card has a very short reach (VSR) transponder and an OTN framer which allocates client signals on the OTN-compliant frame format, forward error correction, or detects and handles monitoring data. Each transponder and OTN framer are connected through 16 lanes of 2.5-Gbps or 2.7-Gbps parallel signals compliant with Serdes Framer Interface Level 5 (SFI-5)[(1)].

DESIGN OF TRANSPONDER SUBSYSTEM

Transmitting part

For the light source, the full-band tunable laser of C-band or L-band with integrated control circuit is used at the transmitting part. This laser can output up to 88 different wavelengths when used at the wavelength interval of 50 GHz (0.4 nm).

Two types of lithium niobate ($LiNbO_3$: LN) modulators are equipped for RZ-DQPSK coding. Figure 4 shows the block diagram of the RZ-DQPSK modulation coding part with LN modulators. The LN modulators for DQPSK encoding, which are operated with a pair of 21.5-Gbps signals pre-coded by OTN framer, etc. as in-phase data or quadrature-phase data, encodes 43-Gbps DQPSK signals. The LN modulator for RZ modulation carries out modulation with the duty ratio of 50% on DQPSK modulated codes and outputs them as optical signals.

An operating circuit with re-timing function is used for operating LN modulators. The circuit is manufactured using Yokogawa's proprietary compound semiconductor technologies, indium phosphide heterojunction bipolar transistor (InP-HBT) process (f_T = 120 GHz, f_{max} = 180 GHz). The circuit has a 4-port output operating capability of 3.8 Vpp. Figures 5 and 6 show the 43-Gbps DQPSK optical waveform and RZ-DQPSK optical waveform, respectively.

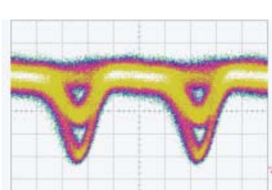

Figure 5 43-Gbps DQPSK Optical Waveform

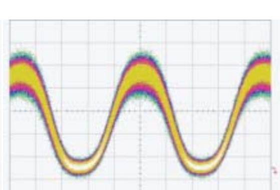

Figure 6 RZ-DQPSK Optical Waveform

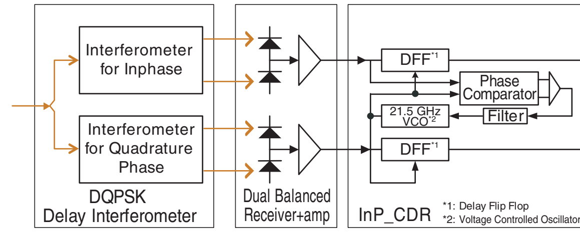

Figure 7 Front End of Receiving Part

Receiving part

The receiving part carries out DQPSK decoding and equivalent amplification by using a pair of balanced receivers containing a DQPSK delay interferometer for DQPSK demodulating and an amplifier circuit, respectively. Figure 7 shows a block diagram of the front end of the receiving part.

The optical signals coded by RZ-DQPSK modulation are input at the front end of the receiving part, divided into 3 dB for demodulation of in-phase data and quadrature-phase data, and input into the interferometer respectively. Divided signals are delayed for 1 bit (approximately 47 ps) and interfered. The interference characteristics of the interferometers for in-phase data and quadrature-phase data are 90 degrees out of phase with each other. These interferometers demodulate the data to the status before pre-coding, using a pair of balanced receivers having a PIN-PD (photodiode) and amplifier circuit. At the Clock Data Recovery (CDR) circuit, clock data is recovered from demodulated signals of 21.5 Gbps × 2 ports.

The photodiodes are manufactured using Yokogawa's InP process, and are characterized by operation in a wide band (≥ 40 GHz) and receiving performance of stable high sensitivity (≥ 0.7 A/W) in the full-band wavelength range. The coupling efficiency between the interferometer and the balanced receiver is 90% or higher. The amplifier circuit and the CDR circuit incorporate integrated circuits which are manufactured by using the above-mentioned InP-HBT process.

Figures 8 and 9 show the output waveform at the 21.5-Gbps operation of the balanced receiver and the CDR circuit, respectively.

External interface part

The external interface of the transponder is compliant with SFI-

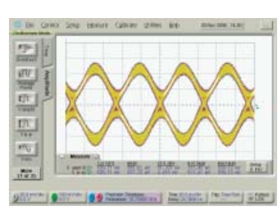

Figure 8 Example of Output Wavelength of Balanced Receiver

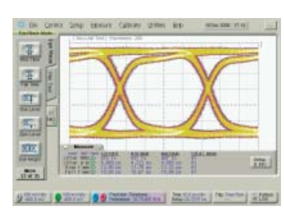

Figure 9 Example of output Wavelength of CDR Circuit

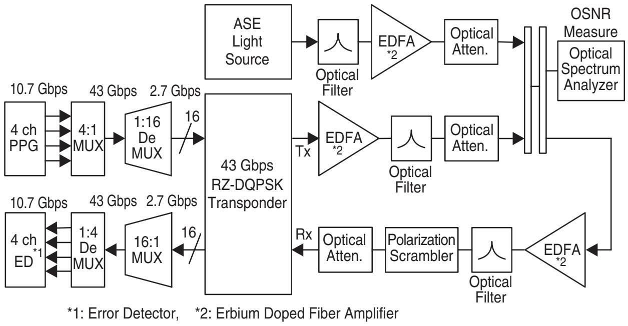

Figure 10 System for Evaluating ASE Noise Immunity

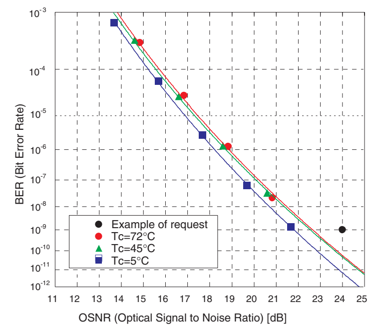

Figure 13 ASE Noise Immunity (0.1 nm Res.)

5 standards and uses industry-standard 300-pin connectors (300-pin MSA: Multi Source Agreement)(2).

Pre-coded electric input signals of 2.7 Gbps in 16 lanes are multiplexed to 21.5 Gbps × 2 ports at the serializer and are input as data to the DQPSK modulator in the transmitting part. Meanwhile, signals demodulated in the transponder to 21.5 Gbps × 2 ports are divided into 16 lanes of 2.7 Gbps at the de-serializer and are output.

The transponder is equipped with optical devices such as LN modulators or delayed interferometers which need to be controlled by sophisticated, complex algorithms. They are controlled and surveyed by the microprocessors in the transponder. The user interface in the transponder such as alarm function or wavelength settings can be monitored or set through serial interface communication (I^2C), and operation commands are compliant with the 300-pin MSA specification.

PERFORMANCE EVALUATION

Evaluation system

Figure 10 shows the evaluation system with 2 × 2 optical couplers on ASE noise immunity of the transponder. The RZ-DQPSK modulated main signal outputs (Tx) are overlapped by ASE noises, the OSNR value of the output is measured using an optical spectrum analyzer, and the output is loop-backed to the receiving side (Rx) of the transponder. A narrow band optical band pass filter (BW ≥ 60 GHz) and a polarization scrambler are installed just before the receiving side (Rx) to examine the performance in almost the same status as during actual operations.

Tolerance to signal waveform distortion owing to chromatic dispersion or polarized mode dispersion is examined by appropriately inserting a variable chromatic dispersion compensator or a DGD element in the signal light path of the evaluation system.

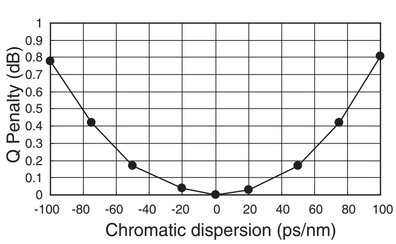

Figure 11 Results of Dispersion Tolerance

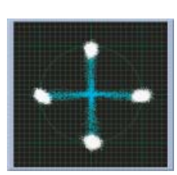

Figure 12 Example of Constellation Measurement

Results of evaluating transmitting performance

Figure 11 shows the results of evaluating the tolerance to chromatic dispersion. The results were sufficient: the penalty was less than 1 dB against dispersion of 100 ps/nm. It was also confirmed that, as transmitting performance, the transponder has good symmetry to positive and negative chromatic dispersions and the optical spectrum occupied by the wave output is adequately small at less than 0.3 nm.

As shown in Figure 12, the Phase Shift Keying (PSK) analyzer revealed that the constellation of the in-phase and quadrature-phase was precisely orthogonally crossed.

Results of evaluating receiving performance

Figure 13 shows ASE noise immunity, which was confirmed to be sufficiently independent of the temperature of the main casing (Tc). As for the requirements for the 40-Gbps system which have been discussed in recent years, the transponder has a certain performance margin. An example of such requirements is OSNR = 24 dB (@ BER = 1×10^{-9})(3).

The results described in this section as well as in section 5.2 confirmed the practicality and effectiveness of RZ-DQPSK modulation.

CONCLUSION

We have successfully developed and commercialized the world's first transponder subsystem by using Yokogawa's proprietary elemental technologies such as InP-centered semiconductor manufacturing and design technologies, optical design and implementation technologies, optical device control technologies, and optical transmission evaluation technologies.

These results will be useful for developing transponders of over 100-Gbps RZ-DQPSK for photonic networks. ◆

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(3) Greg Raybon et al., OFC/NFOEC2008, OTuG1