Demonstration of 10-Gbit/s transmission over G.652 fiber for T-band optical access systems using quantum-dot semiconductor devices

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Abstract: The wavelength range of 1000–1260 nm, known as T-band, where T denotes “thousand”, is one of the promising wavebands suitable for the future moderate-range optical networks. We have developed T-band specific semiconductor devices based on quantum-dot technology. However, the cut-off wavelength of optical fiber cables currently utilized in access networks, i.e., G.652 fibers, is specified to be less than 1260 nm. Therefore, the fibers do not fully support the T-band. This letter presents a demonstration of the feasibility of 10-Gbit/s transmission over G.652 fibers in the T-band by experiments.

Keywords: T-band, optical communication, quantum dot, wavelength tunable laser, SOA

Classification: Optical systems

References

- [1] V. Houtsma, *et al.*: “Recent progress on standardization of next-generation 25, 50, and 100G EPON,” *J. Lightwave Technol.* **35** (2017) 1228 (DOI: [10.1109/JLT.2016.2637825](https://doi.org/10.1109/JLT.2016.2637825)).
- [2] K. Sato, *et al.*: “A large-scale wavelength routing optical switch for data center networks,” *IEEE Commun. Mag.* **51** (2013) 46 (DOI: [10.1109/MCOM.2013.6588649](https://doi.org/10.1109/MCOM.2013.6588649)).
- [3] N. Yamamoto and H. Sotobayashi: “All-band photonic transport system and its device technologies,” *Proc. SPIE* **7235** (2009) 72350C (DOI: [10.1117/12.72350C](https://doi.org/10.1117/12.72350C)).

- 816812).
- [4] N. Yamamoto, *et al.*: “10-Gbps, 1- μ m waveband photonic transmission with a harmonically mode-locked semiconductor laser,” *Opt. Express* **16** (2008) 19836 (DOI: [10.1364/OE.16.019836](https://doi.org/10.1364/OE.16.019836)).
 - [5] N. Yamamoto, *et al.*: “Simultaneous 3×10 Gbps optical data transmission in 1- μ m, C-, and L-wavebands over a single holey fiber using an ultra-broadband photonic transport system,” *Opt. Express* **18** (2010) 4695 (DOI: [10.1364/OE.18.004695](https://doi.org/10.1364/OE.18.004695)).
 - [6] N. A. Idris, *et al.*: “Full-mesh T- and O-band wavelength router based on arrayed waveguide gratings,” *Opt. Express* **24** (2016) 672 (DOI: [10.1364/OE.24.000672](https://doi.org/10.1364/OE.24.000672)).
 - [7] N. A. Idris, *et al.*: “A WDM/TDM access network based on broad T-band wavelength resource using quantum dot semiconductor devices,” *IEEE Photon. J.* **8** (2016) 7901510 (DOI: [10.1109/JPHOT.2016.2520831](https://doi.org/10.1109/JPHOT.2016.2520831)).
 - [8] R. Kubo, *et al.*: “Experimental demonstration of 4K-UHD video transmission using T-band wavelength routing system for passive optical local area networks,” *ECOC* (2017) Th.2.B.4 (DOI: [10.1109/ECOC.2017.8346062](https://doi.org/10.1109/ECOC.2017.8346062)).
 - [9] R. Kubo, *et al.*: “T/O-band wavelength routing system using quantum dot semiconductor devices and 1081-channel AWG router,” *OFC* (2018) Th3H.4 (DOI: [10.1364/OFC.2018.Th3H.4](https://doi.org/10.1364/OFC.2018.Th3H.4)).
 - [10] ITU-T Recommendation G.652: “Characteristics of a single-mode optical fibre and cable,” (2016).

1 Introduction

Optical communication technology utilizing single-core and single-mode optical fibers, which can transmit optical signals at speeds over 100 Gbit/s, is currently being developed to support the increase in network traffic [1, 2]. In particular, the combined utilization of wavelength division multiplexing (WDM) and intensity modulation direct detection (IMDD) techniques for each wavelength is one of the promising solutions to achieve high-capacity, cost-effective, and low-latency optical networks. Recently, these techniques have been applied to moderate-range optical networks, such as access and data center networks. However, the wavebands used in optical communications have mostly been limited to the C-, L-, and O-bands, due to the transmission loss and dispersion of silica optical fibers.

Yamamoto *et al.* [3] proposed the concept of all-band photonics for future optical communication systems, with the aim to develop semiconductor devices operable in the wavelength range of 1000–2000 nm. As shown in Fig. 1, the wavelength range of 1000–1260 nm, known as T-band, where T denotes “thousand”, which is one of the undeveloped wavebands for optical communications, can exploit more than 1000 wavelength channels with 50-GHz spacing. The T-band is expected to be utilized for future access and data center networks, because the transmission loss and dispersion of the optical fibers are not limiting factors in such short reach transmission.

10-Gbit/s transmission experiments have been performed in the T-band over single-mode holey fibers, which cover the T-band [4, 5] and simultaneous transmission was demonstrated in the T-, C-, and L-bands [5]. In addition, to realize a 1000-channel class wavelength routing system using the T-band and the adjacent

Fig. 1. Wavelength bands in optical communication.

O-band, we have developed T/O-band-specific quantum-dot wavelength tunable lasers (QD-WTLs), quantum-dot semiconductor optical amplifiers (QD-SOAs), and arrayed waveguide gratings (AWGs) [6, 7]. We demonstrated 4K ultra-high-definition (UHD) video transmission in the T-band [8] and 10-Gbit/s transmission using the subset of the 1081-channel AWG router, which covers the broad wavelength range of the T/O-band [9].

In the previous transmission experiments in the T-band, T-band specific single-mode optical fiber cables have been used with cut-off wavelengths less than 1000 nm. However, the cut-off wavelength of optical fiber cables currently deployed in access networks, i.e., G.652 fibers, is specified to be less than 1260 nm [10]. If we consider that the T-band is applied to access networks of up to 20 km, it is important to use the existing fibers, which do not fully support the T-band. This letter presents a demonstration of the feasibility of 10-Gbit/s transmission over G.652 fibers in the T-band by experiments.

2 T-band specific devices and G.652 fibers

We developed gain chips mounted on the QD-WTLs and QD-SOAs based on quantum-dot technology. The developed gain chips have broadband capabilities covering the T/O-band with three elements, stable operational capability in high-temperature environments of 95 °C or higher, and reliable operational capacities of 1 million hours or more.

Three kinds of QD-WTLs and QD-SOAs were used in the experiments [9]. QD-WTLs #1, #2, and #3 covered 1030–1120 nm, 1115–1177 nm, and 1207–1300 nm, respectively. The wavelength switching time of the QD-WTLs was less than 200 ms, their spectral line width was less than 300 kHz, and the side mode suppression ratio was greater than 50 dB. QD-SOAs #1, #2, and #3 covered the wavelength ranges of QD-WTLs #1, #2, and #3, respectively, and QD-SOA #3 was a commercially available product. The peak gains of QD-SOAs #1, #2, and #3 were approximately 12 dB, 13 dB, and 15 dB, respectively.

The experimental system is shown in Fig. 2. The T-band specific lithium niobate (LN) intensity modulator and G.652 fibers were commercially available products. The chirp α -parameter of the modulator was specified as less than 0.1. In the experiments, we used four 5-km fiber cables. The cut-off wavelengths of the fibers varied in the range of 1130–1190 nm, which were less than 1260 nm.

Fig. 2. Experimental system for 10-Gbit/s transmission.

3 Transmission experiments over G.652 fibers

The 10-Gbit/s transmission experiments were performed by using the T-band specific devices and G.652 fibers to confirm the feasibility of the T-band optical access system.

3.1 Experimental setup

The experimental setup is shown in Fig. 3. The transmitter was comprised of a QD-WTL, LN modulator, and QD-SOA. The optical output of the QD-WTL was modulated using a pseudo random binary sequence (PRBS) with a sequence length of $2^{15} - 1$ at 10 Gbit/s, generated by a pulse pattern generator (PPG). The modulated signals were fed to the QD-SOA. The output signals of the transmitter were transmitted over the fiber cable. The length of the fiber cable was varied as 0, 5, 10, 15, and 20 km. A variable optical attenuator (VOA) was inserted in the transmission line, the signals were detected by an optical receiver, and the bit error rate (BER) performance was measured by an error detector (ED). A commercialized InGaAs PIN photodiode (PD) was used as the detector in the receiver. The receiver was comprised of the PD, transimpedance amplifier (TIA), limiting amplifier (LA), and clock data recovery (CDR). No optical filters were implemented.

Fig. 3. Experimental setup.

We measured the BER performance of the 10-Gbit/s transmission using four wavelengths: $\lambda_1 = 1069.8$ nm, $\lambda_2 = 1090.0$ nm, $\lambda_3 = 1124.0$ nm, and $\lambda_4 = 1259.8$ nm. The wavelengths λ_1 , λ_2 , and λ_3 were less than the cut-off wavelength, while λ_4 was greater than the cut-off wavelength. When λ_1 and λ_2 were used, QD-WTL #1 and QD-SOA #1 were installed in the transmitter. When λ_3 was used, QD-WTL #2 and QD-SOA #2 were installed in the transmitter. When λ_4 was used, QD-WTL #3 and QD-SOA #3 were installed in the transmitter.

3.2 Results

The results of the BER measurement are shown in Fig. 4. Figs. 4(a)–4(d) show the results for λ_1 , λ_2 , λ_3 , and λ_4 , respectively. In each figure, the length of the fiber cable was varied in the range of 0–20 km, “back-to-back” denotes the configuration with 0-km transmission, and “baseline” denotes the configuration without the QD-SOAs and fiber cables.

Fig. 4. Results of the BER measurements.

Error-free transmission was achieved at each wavelength. As can be seen in Figs. 4(a)–4(d), the power penalties between the baseline and back-to-back configurations at $\text{BER} = 10^{-9}$ were less than 1.5 dB. The power penalty in Fig. 4(a) was greater than that in Fig. 4(b) because the noise figure (NF) of QD-SOA #1 was

larger at λ_1 . The power penalties at $\text{BER} = 10^{-9}$ with respect to back-to-back configuration are summarized in Fig. 5. As can be seen in Fig. 5, the results of λ_2 and λ_3 showed penalties of less than 0.6 dB, whereas the results of λ_4 showed negative penalties of less than 0.2 dB. The power output of the QD-WTLs fluctuated within approximately 0.5 dB in the experiments. This indicates that the multi-mode transmission under the cut-off wavelength possibly does not affect the BER performance in the 20-km transmission for λ_2 and λ_3 . Nevertheless, the results of λ_1 showed greater penalties according to the transmission distance. The chromatic dispersions at λ_1 , λ_2 , λ_3 , and λ_4 are approximately -30 , -25 , -20 , and -5 ps/nm/km, respectively. This suggests that wavelength λ_1 is affected by the multi-mode transmission and chromatic dispersion, which results in the degradation of BER performance. While the analysis of mode dispersion needs further study, the 10-Gbit/s transmission over the 20-km G.652 fiber was experimentally demonstrated in the T-band.

Fig. 5. Power penalties with respect to back-to-back configuration.

In addition, we performed a 4K UHD video transmission experiment over the 20-km G.652 fiber using λ_1 . In this experiment, 12G serial digital interfaces (12G-SDIs) were used to connect the video equipment. The 4K UHD video transmission was successfully demonstrated in the T-band.

4 Conclusion

This letter presented a demonstration of the 10-Gbit/s transmission over G.652 fibers in the T-band as a possible application of the waveband to optical access systems. We measured the BER performance in the transmission experiments using wavelengths under the cut-off wavelength. In the experiments, 20-km transmission was achieved for all wavelengths, and 4K UHD video transmission was also demonstrated. Therefore, the feasibility of the T-band optical access systems was confirmed.

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