Study on Laser-Diode Based Optical Phase-Locked Circuits and Their Application to Multi-Level Coherent Optical Transmission

著者	Wang　Yixin
学位授与機関	Tohoku University
学位授与番号	11301甲第16048号
URL	http://hdl.handle.net/10097/60951

	おう　いしん
氏　　　　　名	王　怡昕
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）電気･通信工学専攻
学位論文題目	LD 型光位相同期回路とその多値コヒーレント伝送への 応用に関する研究
論文審査委員	主査　東北大学教授　中沢　正隆　東北大学教授　山田　博仁 東北大学教授　八坂　洋　東北大学准教授　吉田　真人

論文内容要約

Chapter 1　Introduction

To meet the rapidly growing demand for capacity in optical fiber networks, digital coherent optical quadrature amplitude modulation (QAM) transmission has been intensively investigated. Carrier-phase synchronization between transmitted data and a local oscillator (LO) is very important for this transmission. 2048 QAM transmission has been demonstrated by employing an erbium fiber laser (EFL)-based optical phase-locked loop (OPLL) circuit. By contrast, it has been difficult to realize a low phase noise OPLL circuit with a laser diode (LD) due to its broad linewidth, resulting in the need for an extremely wideband feedback circuit. Therefore, an LD-based OPLL system has not been applied to ultrahigh multi-level QAM transmission.

In this study, low phase noise LD-based optical phase-locked circuits are successfully developed by employing an optical voltage controller oscillator (OVCO) and an injection locking scheme which can realize a wideband feedback control. By applying these circuits to a multi-level QAM coherent transmission, the advantages of these schemes are demonstrated.

Chapter 2　QAM coherent optical transmission

This chapter describes the fundamental configuration and key components of a QAM coherent optical transmission system. Among them, highly precise carrier-phase synchronization is indispensable to realize an ultrahigh multi-level QAM coherent transmission. Here, particular attention is paid to the features and subjects of various optical carrier-phase synchronization technologies. In general, there are two kinds of carrier-phase synchronization technology, a carrier phase estimation method with digital signal processing (DSP) and LO feedback control system with an analog opto-electrical circuit.

Although carrier-phase estimation methods do not require an analog LO feedback system, a computational complexity becomes too high as the multiplicity of the data signal increases. As a result, precise demodulation of a high multiplicity signal becomes difficult. In contrast, the precision of synchronization with analog systems does not depend on the data multiplicity, and therefore it is possible to realize extremely precise carrier-phase locking by expanding the feedback bandwidth.

Chapter 3 LD-based OPLL circuit

This chapter presents a low phase noise OPLL circuit with an OVCO consisting of a 4 kHz linewidth external cavity LD (ECLD), $LiNbO_3$ (LN) phase modulator, an RF-VCO. In a conventional OPLL circuit, where the LO phase was controlled by changing the LD injection current or the external cavity length with PZT, the feedback control bandwidth was limited to several hundred kHz due to the FM-bandwidth of the LD. On the other hand, that of the OVCO-OPLL circuit was independent of LD FM-bandwidth. With the OVCO scheme, the bandwidth was expanded over 4 MHz. As a result, an OPLL with a phase noise as low as 0.6 deg. was successfully realized.

Chapter 4 Optical phase-locked circuit with injection locking

This chapter shows further reduction of OPLL phase noise with an injection locking scheme. Here, it is newly found that there was an optimal value of the injection power to the slave laser which makes the phase noise minimum, and we realized the an extremely low phase noise carrier-phase synchronization.

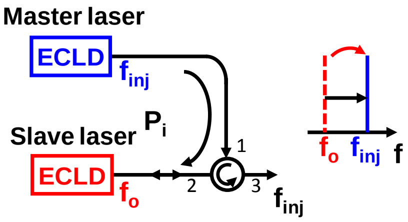
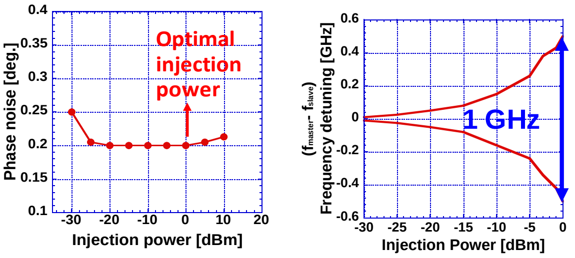


Fig. 1. Schematic diagram of injection locking.



(a) (b)

Fig. 2. (a) Phase noise and (b) locking range as a function of injection power.

Figure 1 shows a schematic diagram of injection locking. Two ECLDs are used both as a master laser and a slave laser. The injection seed from the master laser is injected into the slave laser via a circulator. Under a certain condition, the slave laser is phase-locked to the master laser. The relationship between phase noise and injection power is shown in Fig. 2 (a). With an injection power from -30 dBm to 0 dBm, the phase noise is as low as 0.2 degrees. If the injection power is above 0 dBm or below -30 dBm, the locking becomes unstable. The locking range of the ECLD is expanded as the injection power increases as shown in Fig. 2 (b). From the two experiment results, it is found that the optimal injection power is 0 dBm, where an injection locking scheme with a locking range as wide as 1 GHz and an extremely low phase noise of 0.2 deg is realized.

Compared with an OVCO-based OPLL, the control bandwidth is largely increased from 4 MHz to 1 GHz, and the phase noise is reduced from 0.6 deg. to 0.2 deg. The present phase synchronization scheme also features a simple and compact configuration, which is attractive for application to coherent transmission.

By employing the OVCO-OPLL circuit and the injection locking circuit, 64 and 128 QAM coherent transmissions were successfully demonstrated. This chapter shows their transmission results and clarified the advantages of the analog phase synchronization circuits.

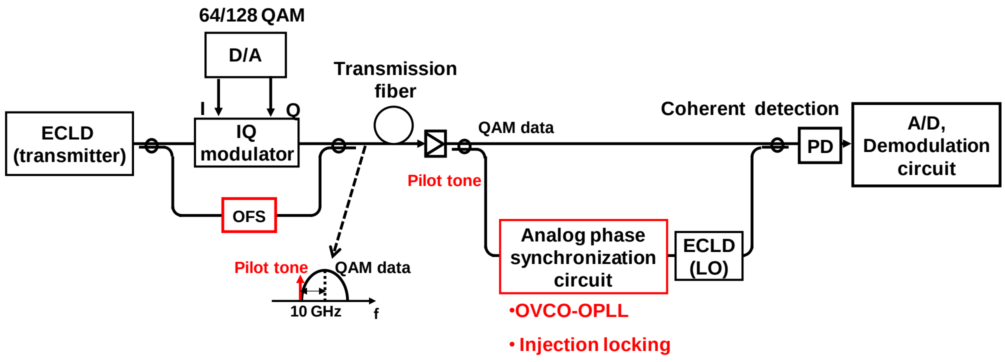
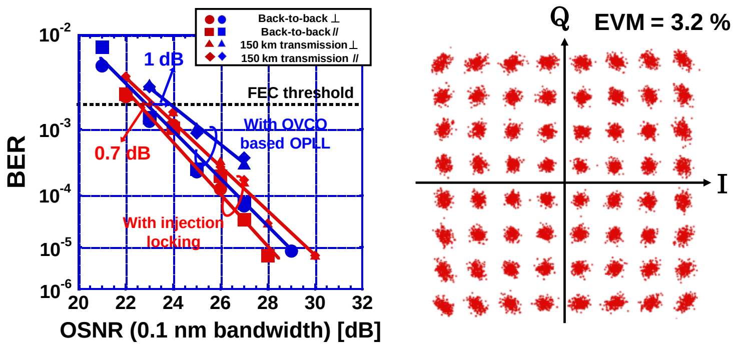


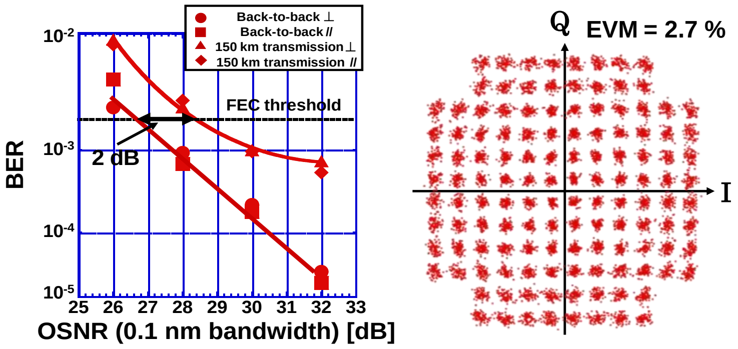
Fig. 3. Configuration of coherent transmission system with analog phase synchronization circuit.

Figure 3 shows a fundamental configuration of QAM coherent transmission. Here, 4 kHz linewidth ECLDs are used both as a transmitter and an LO. At a transmitter part, a polarization-multiplexed 10 Gsymbol/s, 64 or 128 QAM data signal and a pilot tone signal are generated simultaneously. After transmission, the LO is phase-locked to the transmitted QAM data with the tone signal by using the analog phase synchronization circuit. After that, the QAM data signal is homodyne-detected with the LO, and then demodulated with DSP in an offline condition followed by A/D conversion.



(a) BER characteristics (b) Constellation map after transmission with injection locking.

Fig. 4. Transmission results of 64 QAM coherent transmission.



(a) BER characteristics (b) Constellation map after transmission

Fig.5. Transmission results of 128 QAM coherent transmission.

Figure 4 (a) shows the bit error rate (BER) characteristics of the 120 Gbit/s, 64 QAM 150 km transmission using the OVCO-OPLL circuit and the injection locking circuit. The demodulation performance was successfully improved with the injection locking circuit compared with that obtained with the OVCO-OPLL circuit. This is attributed to its wider locking bandwidth resulting in a low phase noise synchronization operation. Figure 4 (b) shows the constellation map of 64 QAM coherent transmission with an injection locking scheme. The error vector magnitude (EVM) is 2.7 %, and an error free transmission is realized. Furthermore, the injection locking scheme made it possible to increase the QAM multiplicity to the 128 QAM, and a 140 Gbit/s signal was transmitted over 150 km. The BER characteristics and the constellation map of the 128 QAM coherent transmission are shown in Fig. 5. This is the highest multiplicity and bit rate yet obtained with an injection-locked coherent transmission using an LD.

Chapter 6 Conclusion

This chapter summarizes the experimental results obtained in this study including two types of analog phase synchronization circuits and their application to coherent transmission. Finally, this chapter discusses future perspective for QAM coherent transmission with higher multiplicity by employing an injection locking circuit.