Device Requirements for Next Generation Optical Transmission Technology

Masataka Nakazawa
Research Institute of Electrical Communication, Tohoku University, Sendai, Japan
nakazawa@riec.tohoku.ac.jp

***Abstract*— We describe fundamental optical devices for ultrahigh-speed and ultra-multilevel coherent optical transmission in the next generation. Key components such as ultrashort and coherent optical sources, advanced optical modulators, ultrafast switches and coherent receivers are overviewed, and their application to 640 Gbit/s/channel OTDM and 256 QAM transmissions are presented.**

Keywords- Ultrahigh-speed OTDM transmission; coherent QAM transmission; mode-locked laser; all-optical switch; frequency-stabilized laser; IQ modulator; OPLL; coherent receiver

I. INTRODUCTION

Two trends have recently emerged in optical communication technology. One is ultrahigh-speed transmission using ultrashort pulses, which is the driving force behind attempts to realise an advanced high-speed optical network. The other trend is ultrahigh spectral density coherent transmission employing multi-level modulation formats, whose aim is to expand the capacity of WDM transmission systems within a finite transmission bandwidth. These advanced optical transmission technologies are enabled by the progress in light sources, optical modulators, and receivers. In this talk, we present recent progress and future prospects for ultrahigh-speed and coherent optical devices toward Terabit/s OTDM and 256 QAM transmissions.

II. ULTRAHIGH-SPEED OTDM DEVICES

First we describe key devices used in OTDM systems by referring to a 640 Gbit/s/channel-525 km transmission experiment that we demonstrated recently [1]. The experimental set-up is shown in Fig. 1. As an optical pulse source, we used a 40 GHz mode-locked fibre laser (MLFL) that generates a 2.0 ps pulse train. MLFL is an attractive pulse source because of low timing jitter around 100 fs, but because of harmonic mode locking, it suffers from a frequency fluctuation as a result of mode hopping. We developed a mode-hop-free MLFL by installing an etalon in the cavity [2], which greatly improved the stability in the optical phase. To generate an ultrashort pulse for 640 Gbit/s, we employed external pulse compression based on spectral broadening using self-phase modulation in a highly-nonlinear fibre with normal dispersion. After chirp compensation and optical bandpass filtering, a pedestal-free (< – 30 dB), 600 fs pulse train was obtained. It should be noted that the phase coherence is well maintained with this pulse compression scheme as noise-induced modulational instabilities do not occur in a normal dispersion fibre. This property is very important for generating a phase-

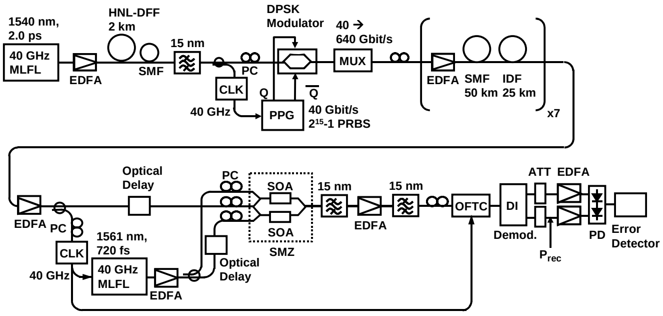

Figure 1. Experimental set-up for a 640 Gbit/s-525 km DPSK transmission.

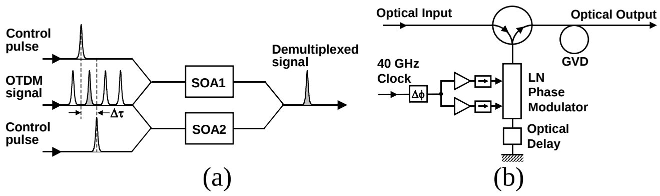

Figure 2. Basic configuration of ultrafast SMZ switch (a) and OFTC (b).

modulated data signal with a subpicosecond pulse. The compressed pulse was then DPSK modulated at 40 Gbit/s and multiplexed to 640 Gbit/s in a single polarisation

After 525 km transmission, the 640 Gbit/s OTDM signal was demultiplexed to 40 GHz with an all-optical semiconductor symmetric Mach-Zehnder (SMZ) switch [3]. The basic configuration of the SMZ switch is shown in Fig. 2(a). By canceling the slow relaxation components of the phase shifts introduced in each SOA with a time delay $\Delta\tau$, an ultranarrow switching gate can be realised. For such an ultrahigh-speed demultiplexing, fibre-based all-optical switches such as a nonlinear optical loop mirror (NOLM) [4] and Kerr switching with parametric amplification [5] have also been demonstrated. Fibre-based switches offer the potential for ultrafast operation owing to a femtosecond response time of the Kerr nonlinearity. The demultiplexed pulse was then launched into an optical Fourier transform circuit (OFTC), in which the spectral profile is converted into a waveform in the time domain and waveform distortions are eliminated [6]. The OFT for a 640 Gbit/s signal was realised by applying a strong chirp to a subpicosecond pulse with a phase modulator operated in a round-trip configuration as shown in Fig. 2(b). Based on this set-up, a bit-error rate (BER) performance sufficiently below a standard FEC threshold ($2x10^{-3}$) for error-free operation was successfully achieved for all OTDM channels.

III. DEVICES FOR ULTRA-MULTILEVEL QAM COHERENT TRANSMISSION

In order to overview fundamental devices for ultra-multilevel coherent transmission, here we describe key components that we adopted in a 256 QAM transmission experiment [7]. The transmission set-up is shown in Fig. 3. As a coherent light source, we employed a C_2H_2 frequency-stabilised fibre laser [8], whose linewidth is 4 kHz and the frequency stability is 1.3×10^{-11}. Recently, a C_2H_2 frequency-stabilised external-cavity laser diode has also been demonstrated with an RIN of –135 dB/Hz and a linewidth of 4 kHz [9]. The coherent light is QAM modulated with an IQ modulator, whose configuration and operation principle are shown in Fig. 4(a). It is composed of three Mach-Zehnder (MZ) inteferometers, in which in-phase (I) and quadrature-phase (Q) data are modulated with MZ_A and MZ_B, respectively, and combined with MZ_C with a 90-deg phase shift between I and Q [10]. In a $LiNbO_3$ (LN)-based IQ modulator, surface acoustic waves generated by the piezoelectric effect in the LN crystal should be suppressed to avoid degradation in the low-frequency response, which is very important for increasing the multiplicity level in QAM transmission. Recently a semiconductor IQ modulator has also been demonstrated using InP as shown in Fig. 4(b) [11], which is beneficial for compact integration. A more complicated IQ modulator can be fabricated using PLC-LN hybrid integration as shown in Fig. 4(c) [12]. After the modulation, the QAM signal is coupled with a pilot tone signal whose frequency is 10 GHz down-shifted against the data signal.

After the transmission, the QAM signal is homodyne-detected with a local oscillator (LO) to convert the QAM data into a baseband signal. Here we employed an optical phase-locked loop (OPLL) technique to lock the optical phase between LO and QAM signal using the transmitted pilot tone, in which a high-speed free-running fibre laser is used as an LO [13]. A configuration of a coherent receiver used for homodyne detection is shown in Fig. 5. The LO output is divided with a 90-deg phase shift each other and coupled with the QAM signal in a 90-deg optical hybrid circuit so that the cosine (I) and sine (Q) components are obtained after balanced detection. The phase noise of the detected signal was as low as 0.3 deg., which is sufficiently small for demodulating a 256 QAM signal. Finally they are A/D converted and demodulated into a binary sequence in the DSP. Because of the software demodulation, this transmission system operates in an off-line condition.

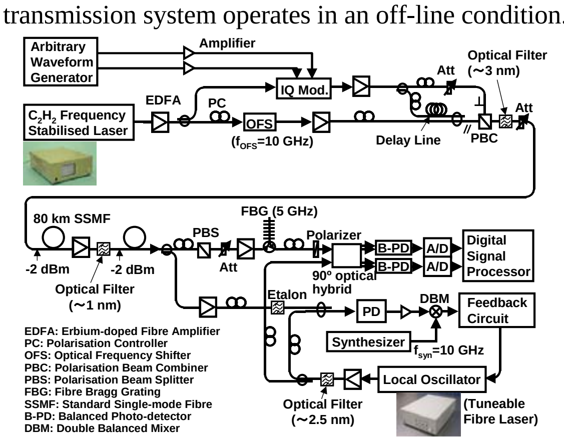

Figure 3. Experimental set-up for 4 Gsymbol/s, 256 QAM transmission.

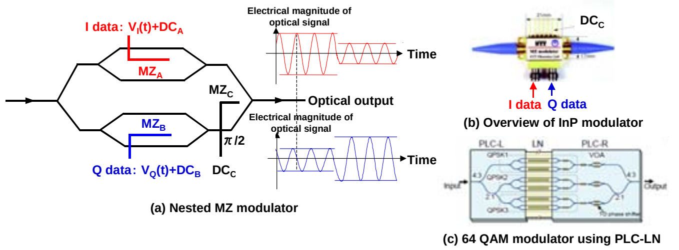

Figure 4. Nested Mach-Zehnder modulators used as an IQ modulator.

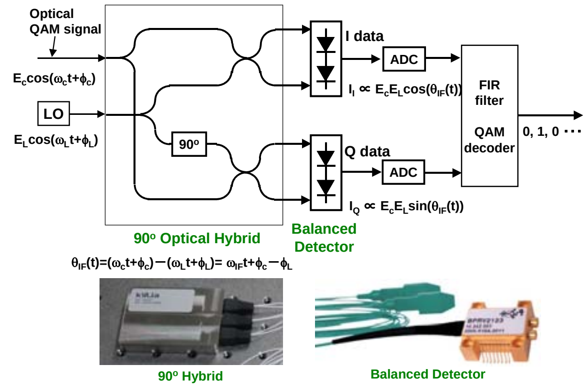

Figure 5. Coherent detection of QAM signal using a 90-deg hybrid and balanced detectors.

In this set-up, we successfully transmitted a polarisation-multiplexed, 4 Gsymbol/s 256 QAM (64 Gbit/s) signal over 160 km within an optical bandwidth of 5.4 GHz, indicating the possibility of spectral efficiency as high as 11 bit/s/Hz. Such an ultrahigh spectral efficiency is substantially beneficial not only for expanding the WDM transmission capacity but also for reducing power consumption.

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