# OCDMA over WDM Transmission

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**ABSTRACT**
The optical code division multiple access (OCDMA) over wavelength division multiplexing (WDM) passive optical network (PON) system has been proposed as a potential candidate for gigabit-symmetric fiber-to-the-home (FTTH) services. Asynchronous OCDMA over WDM systems have been experimentally demonstrated using superstructured fiber Bragg gratings (SSFBG) and multi-port OCDMA en/decoders. The total throughput has reached above ~380 Gbit/s with spectral efficiency of about ~0.32.

**Keywords**: Fiber optics communication; Wavelength division multiplexing, Optical code division multiple access; Multiple access interference; Beat noise; Differential phase shift key; Field trial.

## 1. INTRODUCTION

Optical code division multiple access (OCDMA) technique is an attractive candidate for next generation broadband access networks. Figure 1 illustrates a basic architecture and working principle of an OCDMA passive optical network (PON) network. In the OCDMA-PON network, the data are encoded into pseudo-random optical code (OC) by the OCDMA encoder at the transmitter and multiple users share the same transmission media by assigning different OCs to different users. At the receiver, the OCDMA decoder recognizes the OCs by performing matched filtering, where the auto-correlation for target OC produces high level output, while the cross-correlation for undesired OC produces low level output. Finally, the original data can be recovered after electrical thresholding. Due to the all optical processing for encoding/decoding, OCDMA has the unique features of allowing fully asynchronous transmission with low latency access, soft capacity on demand, protocol transparency, simplified network management as well as increased flexibility of QoS control [1-3]. In addition, since the data are encoded into pseudo-random OCs during transmission, it also has the potential to enhance the confidentiality in the network [4-6].

Recently, coherent OCDMA technique, where encoding and decoding are based on the phase and amplitude of optical field instead of its intensity, is receiving much attention for the overall superior performance over incoherent OCDMA and the development of compact and reliable encoder/decoders (E/D) [7-14]. In these coherent OCDMA systems, an ultra-short optical pulse is either spectrally encoded time-spread (SPECTS) by high resolution phase E/D [8] or spatial light phase modulator (SLPM) [9-10], or directly time-spread encoded by superstructured fiber Bragg grating (SSFBG) [11-13] or multi-port E/D with waveguide grating configuration [14-15].

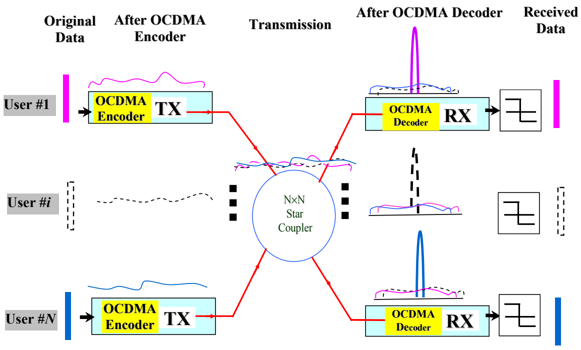


*Fig.1 .Working principle of OCDMA PON network.*

On the other hand, wavelength division multiplexing (WDM) is a very successful technique in current fiber optic communication systems. Hybrid WDM/OCDMA network has been proposed as a prospective candidate for future broadband access network that can support gigabit-symmetric FTTH services [16-18]. In this paper, we present several experimental demonstrations of the OCDMA over WDM system based on SSFBG and multi-port E/D.

## 2. OCDMA OVER WDM EXPERIMENT USING SSFBG

The auto-correlation performance of a pair of SSFBG encoder/decoder is very sensitive to the wavelength mismatch between them [13, 16]. Therefore, we proposed a hybrid OCDMA over WDM system whose architecture is shown in Fig. 2. In this system, the SSFBG serves as OCDMA E/D as well as WDM multiplexer/demultiplexer simultaneously to simplify the configuration. The OCs could be reused in different

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WDM channels and the channel spacing can be much narrower than the chip-rate to enhance the spectral efficiency [17].

Figure 3 shows the setup of a 3-wavelength OCDMA over WDM experiment using 511-chip, 640 Gchip/s SSFBGs. The pulse train generated from the mode-locked-laser-diode (MLLD) has central wavelength of 1550.8 nm and repetition rate 10 GHz. This signal was modulated by $2^{23}$-1 pseudo-random bit sequence (PRBS) at 1.244 Gbps with lithium niobate intensity modulators (LN-IMs) and pulse pattern generators (PPGs). The amplified signal was split and encoded by SSFBG encoders with central wavelength of 1550 nm, 1550.8 nm and 1551.6 nm to generate the WDM/OCDMA signals. The "user adjust" units, which consist of fixed fiber delay line with different length, tunable optical delay line (TODL), tunable optical attenuator with switch and polarization controller (PC), were used in each path to investigate the system performance in different scenario. Particularly, the system was tested in the worst-case scenario with synchronous bit phase and aligned polarization state to guarantee asynchronous operation [4]. This setup could emulate up to 16 active users ($K$ = 16) totally in 3 wavelengths.

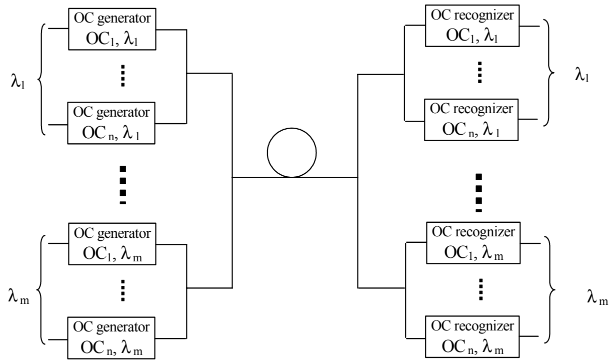


*Fig. 2. OCDMA over WDM system architecture*

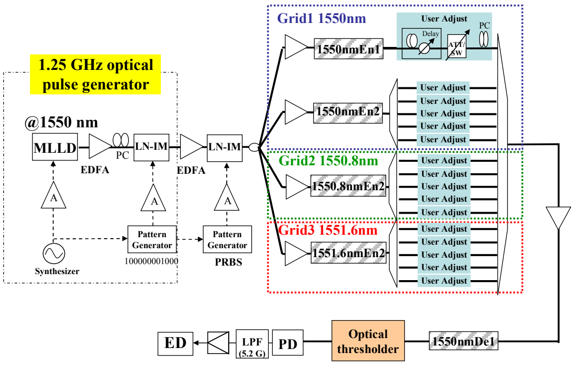


*Fig. 3 Experimental setup.*

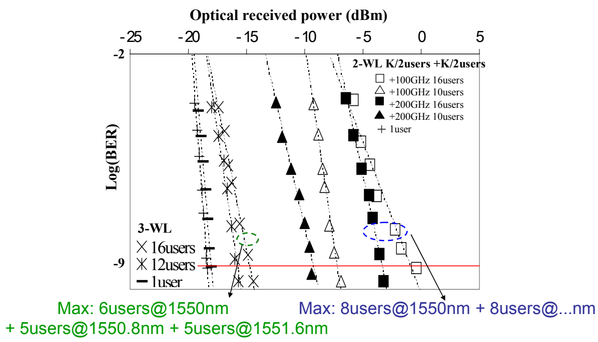


*Fig. 4. BER performance.*

The multiplexed signals were amplified and decoded by SSFBG decoder with central wavelength of 1550 nm. An optical thresholder based on cascaded second-harmonic-generation (SHG) and differential-frequency-generation (DFG) in periodically-poled-lithium-niobate (PPLN) was employed to suppress the multiple-access-interference (MAI) and the photodiode (PD) followed by a 5.2 GHz low-pass-filter (LPF) was used to perform data-rate detection. The bit error rate (BER) was measured by error detector (ED). Fig. 4 shows measured BERs for single-, 2- and 3-wavelength experiments. In single wavelength case, the maximum number of active users K for error free (BER < $10^{-9}$) is 10, which agrees with previous results [19]. In 2- and 3-wavelengths experiments, error free for $K$ = 16 has been be achieved. There are very little power penalty between K=16 and K=1 showing that more active users could be supported in the hybrid WDM/OCDMA system.

## 3. FIELD TRIAL OF HYBRID WDM/OCDMA EXPERIMENT USING MULTI-PORT E/D

Figure 5 shows another proposed architecture of cost-effective WDM/OCDMA network, which uses a large scale multi-port E/D in the central office, and a low cost E/D in the ONU. The multi-port E/D has very high power contrast ratio (PCR) between auto- and cross-correlation signals, which can significantly suppress MAI and beat noise with a short OC [15]. The multi-port E/D with periodic spectral response can process multiple OCs in multiple wavelength bands with single device as shown in the inset, and the cost will be shared by all the subscribers. At the ONU side, fixed SSFBG or TVF can be

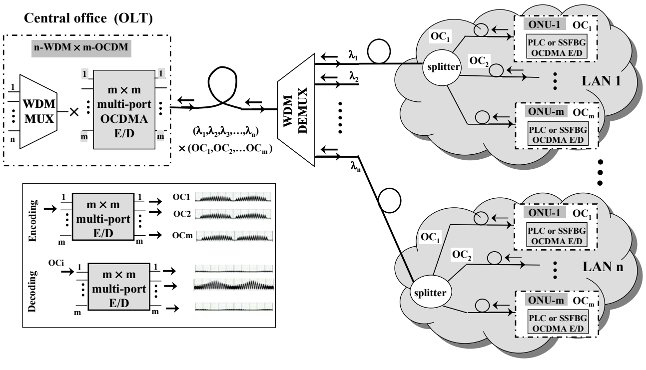


*Fig.5. Proposed WDM/OCDMA network architecture.*

used as the low cost E/D. The hybrid using of multi-port E/D as encoder and transversal-filter-(TVF) type decoder also has very high PCR that is one key to enable multi-user asynchronous OCDMA by suppressing the noises [18].

Figure 6 shows the setup for experimental demonstration of the proposed scheme in a field trial. Three MLLDs generated 3 WDM pulse signals with about 3.2 nm (400 GHz) channel spacing. The generated ~1.8ps optical pulses are at a repetition rate of 10.709 GHz with central wavelengths of 1550.2 nm, 1553.4 nm and 1556.6 nm, respectively. Each signal was modulated by Lithium Niobate phase modulator (LN-PM) separately with $2^{31}$-1 PRBS from independent data sources. The signals were then multiplexed and go to the port #1 of the 16×16 ports E/D. Inset α shows the spectrum of this multiplexed signal. 16 different OCs were generated at the 16 output ports. Inset β shows the waveform of the mixed signals of 3 WDM, 12 OCDMA users. This signal was then launched into 100 km SMF installed in the field between our laboratory in Koganei city and Otemachi of downtown Tokyo in a loop-back configuration. The WDM×OCDMA signal was then de-multiplexed by the WDM DEMUX with 400 GHz channel spacing, and further transmitted thru ~11 km SMF before arrived in the 16-chip programmable TVF-type decoder. The decoder was programmed to decode four different OCs correspond to those of encoder ports 4, 8, 12, 16. A fiber based interferometer and balanced detector perform the differential-phase-shift-key (DPSK) detection. The data was finally tested by the BER tester with clock signal from the clock-data-recovery (CDR) circuit.

Fig. 7 shows the measured BER performances as well as several eye diagrams. Fig. 7*a* shows those for 4 different decoders with 3 WDM, single and 12 active OCDMA users ($K$ = 1, 12) in back-to-back (B-to-B) case. Error-free has been achieved for all the OCDMA users in 3 WDM channels. The average power penalty for $K$ = 12 to $K$ = 1 is about 8 dB. Fig. 7*b* shows that error free has been successfully achieved for all the 4 decoders with 3-WDM and up to 10 OCDMA users in the field trail. The spectral efficiency (η) is about 0.32 and 0.27 bit/s/Hz for B-to-B and field transmission, respectively, which are very high for asynchronous OCDMA.

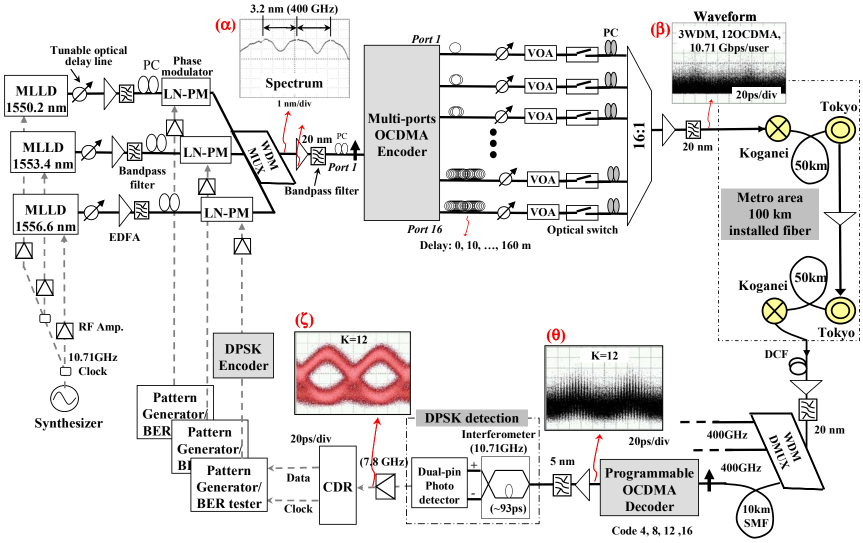


Fig. 6. Experimental setup.

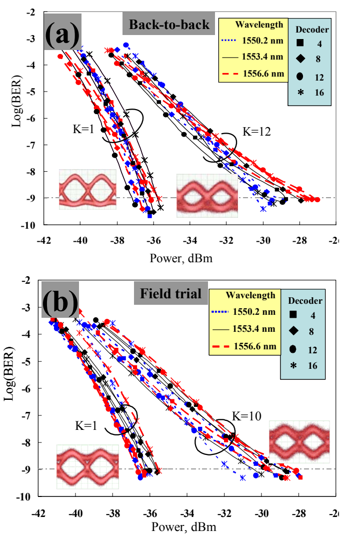


Fig. 7. BER performance.

## 4. CONCLUSIONS

Hybrid asynchronous WDM/OCDMA system using SSFBG or multi-port E/D has been proposed and experimentally demonstrated. It is one prospective candidate for future broadband access network that can support gigabit-symmetric FTTH services. Employing DPSK modulation with balanced detection can significantly enhance the multi-user capability of the system and hybrid using of different kinds of E/D makes the system more flexible and cost-effective. Furthermore, spectral efficient asynchronous OCDMA can be achieved by using a large scale multi-port E/D with higher PCR, polarization multiplexing and forward-error-correction (FEC) [20].

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