

Hybrid WDM/OCDMA for Next Generation Access Network

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ABSTRACT

Hybrid wavelength division multiplexing/optical code division multiple access (WDM/OCDMA) passive optical network (PON), where asynchronous OCDMA traffic transmits over WDM network, can be one potential candidate for gigabit-symmetric fiber-to-the-home (FTTH) services. In a cost-effective WDM/OCDMA network, a large scale multi-port encoder/decoder can be employed in the central office, and a low cost encoder/decoder will be used in optical network unit (ONU). The WDM/OCDMA system could be one promising solution to the symmetric high capacity access network with high spectral efficiency, cost effective, good flexibility and enhanced security. Asynchronous WDM/OCDMA systems have been experimentally demonstrated using superstructured fiber Bragg gratings (SSFBG) and multi-port OCDMA en/decoders. The total throughput has reached above Tera-bit/s with spectral efficiency of about 0.41. The key enabling techniques include ultra-long SSFBG, multi-port E/D with high power contrast ratio, optical thresholding, differential phase shift keying modulation with balanced detection, forward error correction, and etc. Using multi-level modulation formats to carry multi-bit information with single pulse, the total capacity and spectral efficiency could be further enhanced.

Key words: Optical code division multiple access, Wavelength multiplexing, inter-channel cross-talk, multiple access interference, fiber Bragg grating, arrayed waveguide grating, forward error correction

I. BACKGROUND

Passive optical network (PON) provides a solution for the first/last mile bottleneck in telecommunications infrastructure between the service provider central office, head-end or point-of-presence, and business or residential customer premises. The rapid traffic growth in access network driving by triple play services (such as high-speed internet, IP telephony, and broadcasting video) creates the demand for abundant uplink bandwidth. In the upgrading scenario in the near future, therefore, in order to meet the bandwidth requirements, a high bit rate uplink is a requisite, leading to a proposal of the system concept of Gigabit-symmetric FTTH [1].

Time-division-multiplexing (TDM) PONs such as ATM PON and Ethernet PON (E-PON) have been currently deployed. However, in such TDM PONs time-sharing transmission in the uplink limits the bandwidth of individual users. It would be difficult for TDMA-based PON system to provide gigabit class bandwidth with the uplink simultaneously to all the customers due to the nature of time-slot-based multiple access. It will also difficult to provide the services to the customers with different bit rates in the uplink.

Wavelength division multiple access (WDMA) technique, where different users are assigned with different wavelengths using multiplexer/demultiplexer (MUX/DEMUX), is a natural approach to enhance the uplink capacity. As it is shown in Fig. 1(a), WDM PON creates point-to-point links between OLT and each user, thus solving the bandwidth

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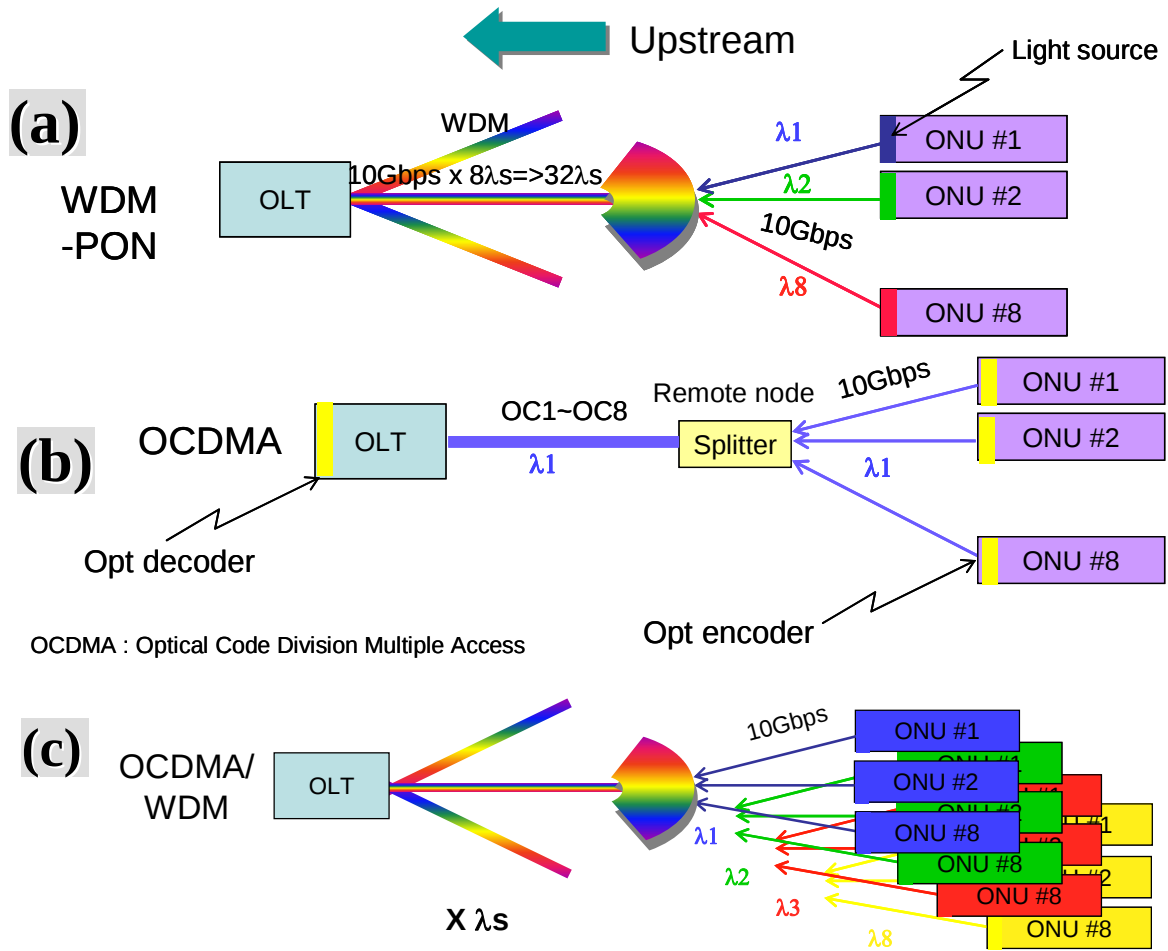


Fig. 1 Architecture of (a) WDM PON (b) OCDMA PON (c) OCDMA/WDM PON

scarcity problem of TDMA PONs. A smooth migration to WDMA from TDM PONs is expected for the service providers in the near future if the mass productivity and the common specifications can reduce the cost of the ONU. However, the number of the wavelengths is not sufficient for the multiple access system which accommodates even a moderate number of users if an individual wavelength is uniquely assigned to each user.

Optical code division multiple access (OCDMA) technique, which allows multiple users share the same transmission media by assigning different optical codes (OCs) to different users, is an attractive candidate for next generation broadband access networks due to its unique features of allowing fully asynchronous transmission with low latency access, as well as enhanced confidentiality [1~3]. In addition, since the data are encoded using pseudo-random optical codes (OCs) during transmission, it also has the potential to enhance the confidentiality in the network [4~6]. Figure 1(b) illustrates the basic architecture an OCDMA PON. In the OCDMA-PON network, data is encoded into OCs by the OCDMA encoder at the transmitter, and multiple users share the same transmission media by using power splitter/combiner. At the receiver, the OCDMA decoder recognizes the OCs by performing matched filtering, and the auto-correlation for target OC produces high level output, while the cross-correlations for undesired OCs produce low-level outputs. Finally, the original data is recovered after electrical thresholding.

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 en/decoders (E/D) [7~14] like spatial light phase modulator (SLPM), superstructured fiber Bragg grating (SSFBG) and multi-port array waveguide grating (AWG)-type E/D. In 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 a waveguide grating configuration [14~15].

Figure 1(c) shows the architecture of the OCDMA over WDM PON, which could be one promising solution to the symmetric high capacity access network with high spectral efficiency, cost effective, good flexibility and enhanced security [1]. In this architecture, OCDMA channels can be overlayed on WDM grids. On each WDM grid λ_n ($n=1, \dots, N$), M users can be accommodated by individually assigning each user with a different OC $_m$ ($m=1, \dots, M$). The same code sequence OC $_m$ can be reused on all the WDM channels. The total number of users which can be accommodated in the PON becomes $N \times M$. OCDMA over WDM might be viewed in a way that a WDM channel is shared with M users by equally dividing the bandwidth into channels with smaller data granularity. This channel division can be realized in an asynchronous manner without using time-slots, thus clearly differentiated from synchronous access via TDMA.

In this paper, we will review several approaches to achieve the high capacity, cost effective OCDMA/WDM system.

II. OCDMA OVER WDM USING SSFBG

a. Superstructured fiber Bragg grating

A superstructured fiber Bragg grating (SSFBG) is defined as an FBG with a slowly varying refractive-index modulation profile imposed along its length [11-13]. The full complex refractive-index modulation profile can be realized in an SSFBG by inserting phase shifts between different segments, as shown in up left corner of Fig. 2. With an injection of a short optical pulse, this phase-shifted SSFBG can generate a series of coherent short optical pulses whose phases are determined by the pattern of the phase shifts in the SSFBG. If the refractive-index modulation is constant along the whole grating, the light can penetrate the whole grating length, and the individual segments of the grating contribute more or less equally to the reflected response. The phase-shifted SSFBG thus works as an optical transversal filter to generate a binary-phase-shift-key (BPSK) or a quaternary-phase-shift-key (QPSK) optical code from its impulse response, and it can also perform correlation for code recognition. This sort of phase-shifted SSFBG can be fabricated with a single short phase mask by continuous grating writing or holographic techniques. These techniques provide a high flexibility in producing different ultra-long optical code. High-precision phase control can be achieved as well for BPSK, QPSK or even more multiple phase level optical code.

SSFBG encoder/decoder exhibits advantages such as the capability to generate ultra-long optical code with ultra-high chip rate, polarization independent performance, low and code-length independent insertion loss, inherent compatibility with fiber-optic system, high compactness as well as low cost. Fig. 2 also shows a photo of the record-long 511-chip, 640 Gchip/s SSFBG [13]. The chip length and the total length of the gratings were 0.156 mm and 80 mm, respectively, which corresponds to a chip rate of 640-Gchip/s with the generated optical code of about 800 ps. The SSFBG was fabricated by using the holographic technique. The waveforms of generated OC, auto-/cross-correlations are shown in the bottom of Fig. 2, very high distinction ratio has been achieved by these encoder/decoders.

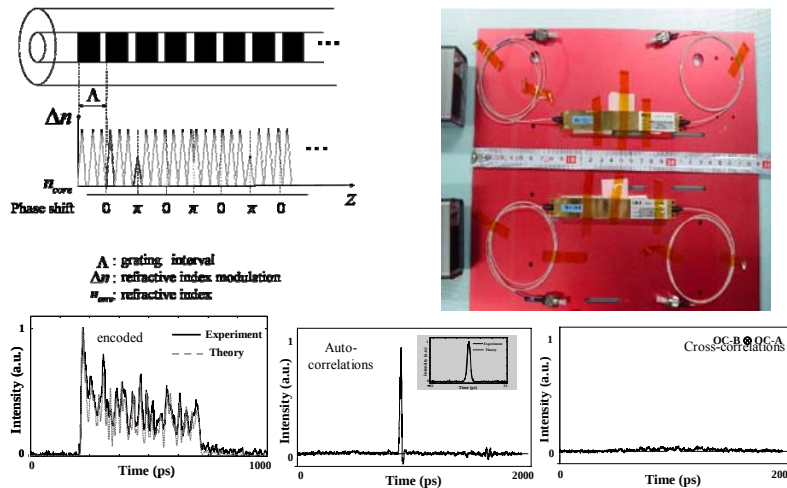


Fig. 2. The configuration of phase-shifted SSFBG

b. OCDMA over WDM using SSFBG

Figure 3(a) shows the spectra of typical SSFBGs. Basically, a SSFBG could function as OCDMA encoder/decoder as well as WDM DEMUX [1, 16]. Figure 3(b) shows the architecture of OCDMA over WDM using SSFBG en/decoders. In this architecture, only low cost power splitters/combiners are used to distribute/multiplexing signals, while the SSFBGs work as OCDMA encoder/decoder as well as WDM DEMUX. So, it could be a cost effective solution for the OCDMA/WDM system. However, in a OCDMA/WDM system, we have to deal not only the multiple access interference (MAI) in OCDMA system [3], but also the WDM inter-channel crosstalk. To lower the inter-channel crosstalk, the channel spacing was suggested to be no less than the chip-rate. Previously, OCDMA over 500-GHz spacing WDM using 255-chip, 320Gchip/s SSFBG encoder has been demonstrated with spectral efficiency of 0.005 bit/s/Hz [17]. Using 511-chip, 640 Gchip/s SSFBG, 10-ch OCDMA transmission on single wavelength has also been demonstrated [18], if we assign the channel spacing equal to the chip rate, the spectral efficiency is ~ 0.02 bit/s/Hz. In either above cases, spectral efficiency is very low. Figure 4 (a)&(b) show the auto-correlation peak against central wavelength mismatch between en/decoder. The auto-correlation peaks are very sensitive to this mismatch, which enable us to narrower the channel spacing lower than chip rate. By making a compromise between channel spacing and the

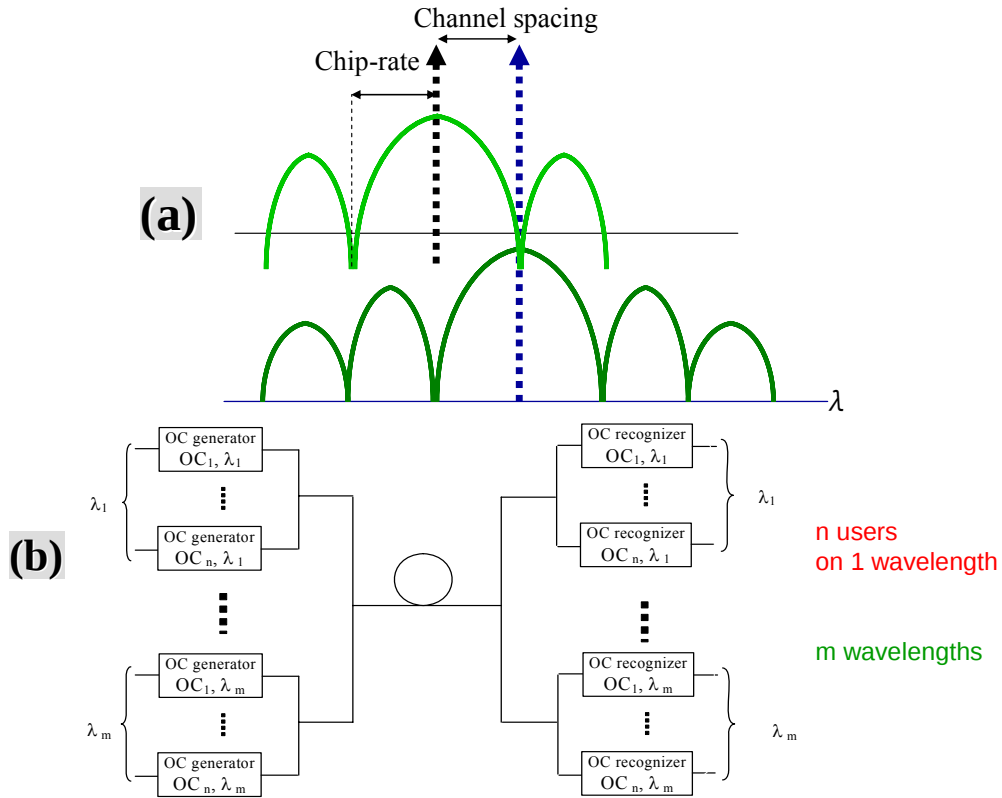


Fig. 3. (a) spectra of SSFBGs (b) architecture of OCDMA over WDM PON using SSFBG

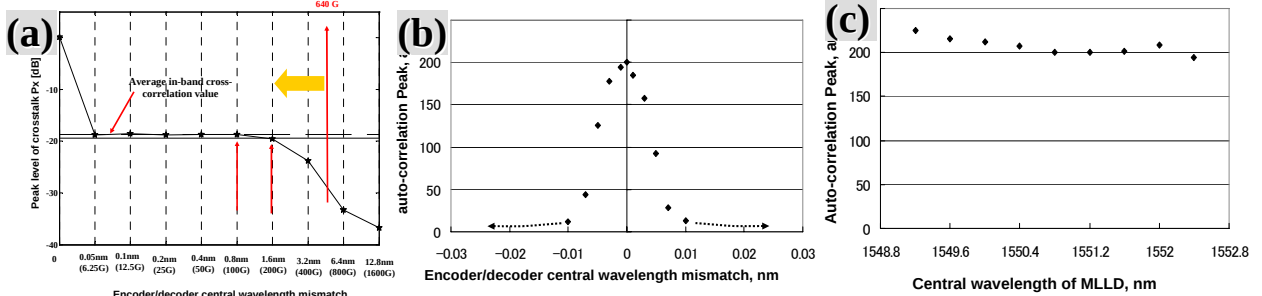


Fig. 4. Autocorrelation peak against central wavelength mismatch between en/decoder (a) Theory (average all codes) (b) measurement (c) Autocorrelation peak against central wavelength of laser source

crosstalk, the spectral efficiency of the system could be enhanced. Figure 4(c) also shows the auto-correlation peak against central wavelength of laser source. The peak is not very sensitive to the wavelength shift. Therefore, a colorless light source can be used, which could make the system more simple and cost effective. We experimentally demonstrated OCDMA over 100-GHz spacing WDM system with single light source, 511-chip, 640 Gchip/s SSFBGs en/decoder, tuned to 1550, 1550.8 and 1551.6 nm respectively.

c. Experimental demonstration

Figure 5 shows the experimental setup. The optical pulse train generated from a single mode-locked laser diode (MLLD) was modulated by $2^{23}-1$ pseudo-random bit sequence (PRBS) at 1.244 Gbps with lithium niobate intensity-modulators (LN-IMs). The amplified signal was split and encoded by 511-chip SSFBG encoders tuned to different wavelengths. Fixed fiber delay line with different length, tunable optical delay line (TODL) and polarization controller (PC) were used to investigate system performance in the worst-case scenario [18]. Tunable attenuator (ATT) with switch was also used to balance the power level from each channel and adjust the number of K. In this experiment, 15 branches were setup after three encoders (1550-nm, 1550.8-nm and 1551.6-nm Code2) to emulate multiple interfering channels. In single user experiments, we used the SSFBG en/decoders tuned to different wavelengths and measured the maximum K that can be accommodated with the error free (BER < 10^{-9}) on different wavelengths. In the 2-wavelength experiments, we demonstrated; (a) single user @1550nm + (K-1) users with the channel spacings of 100GHz (@1550.8nm) and 200 GHz (@1551.6nm), and (b) K/2 users @ 1550nm + K/2 users with the channel spacings of 100 GHz and +200 GHz. In the 3-

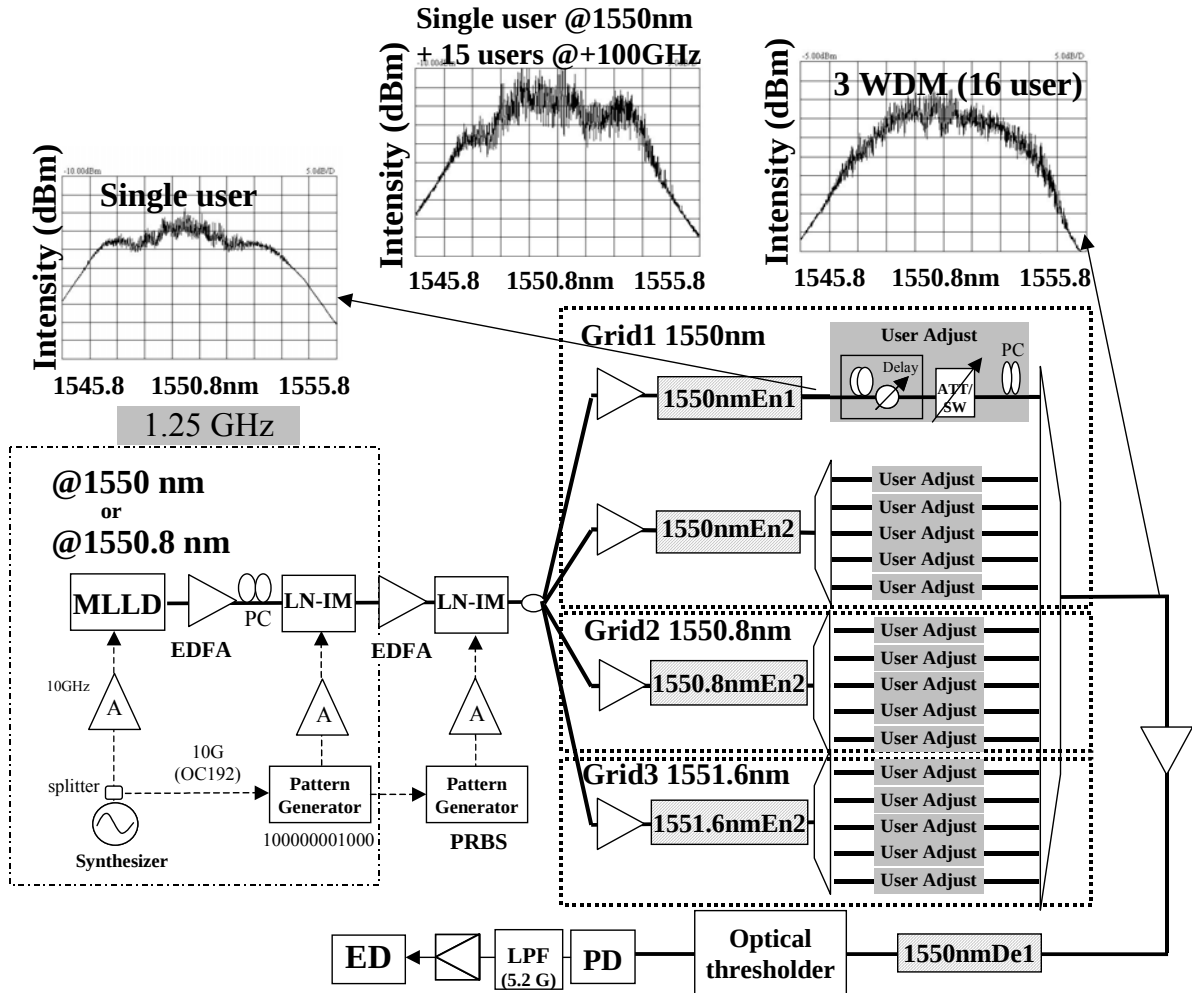


Fig. 5 Experimental setup of OCDMA over 3-wavelength WDM, and spectra of single and 3-WDM (16-user) encoded signals

wavelength experiments, the central wavelength of MLLD was set at 1550.8 and the other two WDM channels were set with ± 100 GHz apart. Multiplexed signals were amplified and an SSFBG decoder decoded the target signal at the given wavelength. Since the received signals suffer from severe MAI as well as inter-channel cross talk, we employed the optical thresholder based on cascaded SHG and DFG in PPLN after the decoder as shown in the lower diagrams of Fig. 6 to suppress the MAI noise. Photodiode (PD) followed by a 5.2 GHz low-pass-filter (LPF) was used to perform data-rate detection, and bit error rate (BER) was finally measured by error detector (ED).

Fig. 7 shows measured BERs for different K in the single-, 2- and 3-wavelength experiments. In single wavelength case, the maximum K is 10 for all the three wavelengths same as our previous results [18]. In two wavelength case with single user at 1550 nm and multiple users at +100 or +200 GHz, 2-wavelength cases with $(K/2 + K/2)$ at +100 or +200 GHz channel spacing and 3-wavelength case, 16-user error free transmission have been achieved. The spectral efficiency can be ~ 0.075 bit/s/Hz, which is more than three times higher than previous. Here, the maximum number of user is limited by the experimental set up. The spectral efficiency could be even higher than this. It is also noteworthy that a single MLLD can cover 5 WDM channels with more than 50 users.

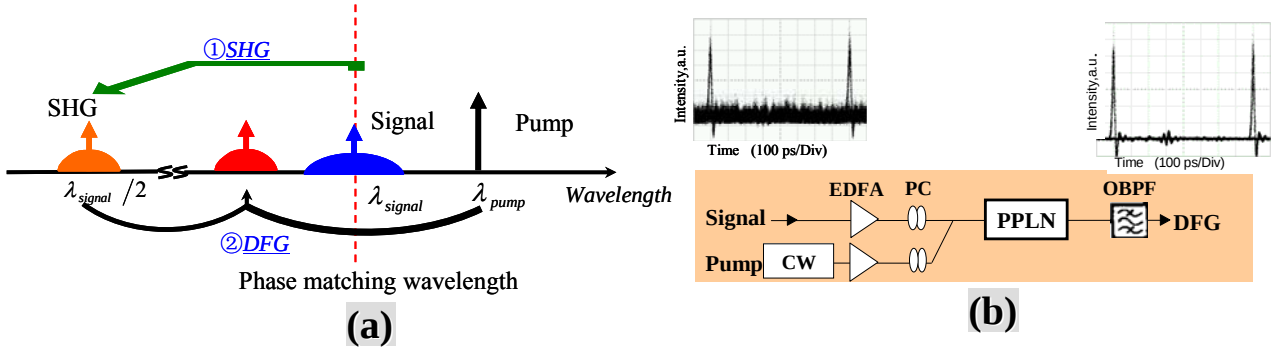


Fig. 6 (a) Working principle, and (b) configuration of optical thresholder based on cascaded SHG and DFG in PPLN

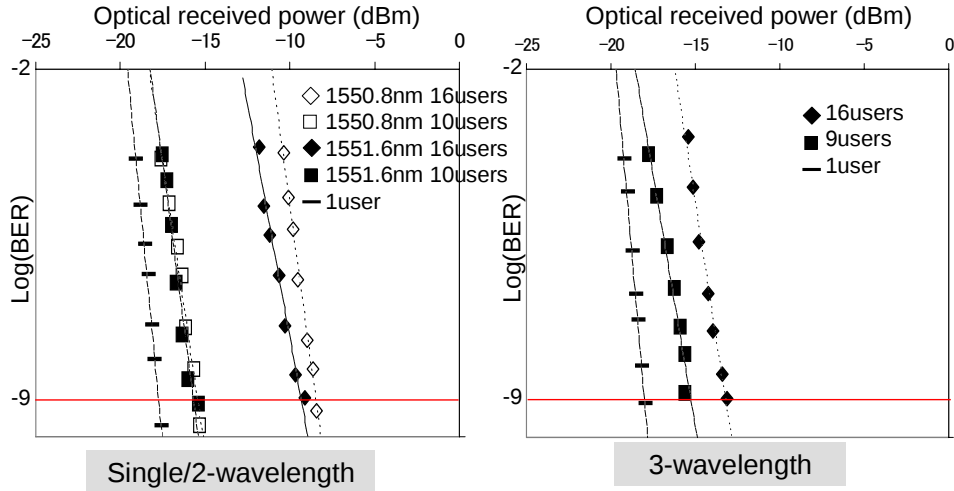
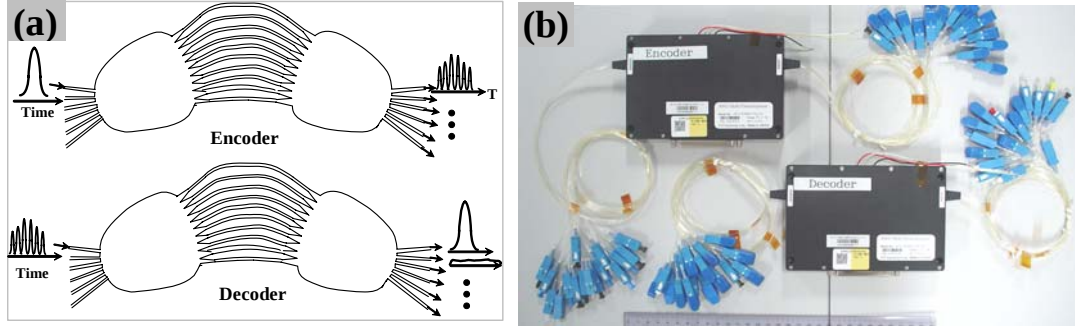


Fig. 7 BER performances

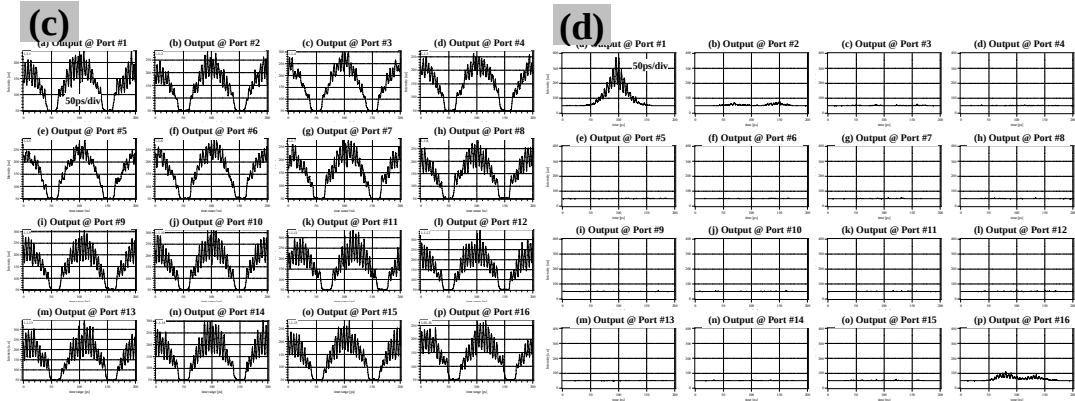
III. OCDMA OVER WDM USING MULTI-PORT ENCODER/DECODER

a. Multi-port encoder/decoder

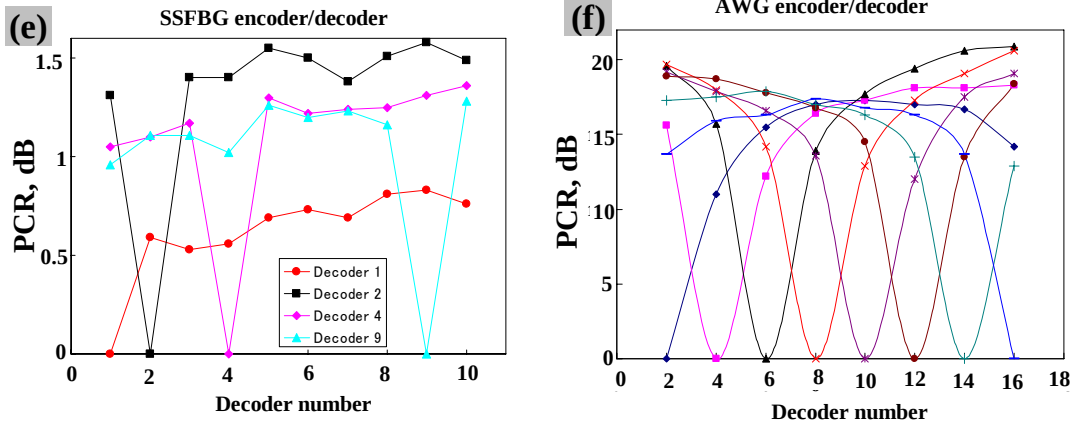
A novel optical code encoder/decoder in an AWG configuration has been proposed originally for optical label processing in an optical packet switching experiment [14~15]. Figure 8(a) shows a schematic diagram of the AWG-based multi-port OCDMA encoder/decoder that is able to simultaneously generate and recognize a set of time-spread



(a) Schematic configuration of AWG-based multi-port OCDMA en/decoder (b) Photos of 16×16 AWG encoder/decoder



(c) Simultaneously generated 16 encoded waveforms (d) Photos Multiple-optical code recognition (input code = #1)



(e) PCR of 511-chip SSFBG encoder/decoders

(f) PCR of the 16×16 AWG encoder/decoders

Fig. 8 Coherent time-spreading OCDMA encoder/decoder in an AWG configuration

optical codes with single device [14]. Figure 8(b) is a photo of a 16×16 ports AWG encoder/decoder. The simultaneously generated 16 optical codes are shown in Fig. 8(c), while Fig. 8(d) shows the waveforms of the auto- and cross-correlations that are simultaneously output from the 16 ports of the decoder. The unique capability of simultaneously processing multiple optical codes with one device makes the AWG encoder/decoder a cost effective device for OCDMA networks to be used in the central office to reduce the number of coding devices. Another attractive feature of the AWG encoder/decoder is that it has very high power contrast ratio (PCR) between auto- and cross-correlation signals compared to other coding devices, such as SLPM and SSFBG. We measured the PCR of the 511-chip, 640 Gchip/s SSFBG and the 16×16 ports, 200 Gchip/s AGW encoder/decoder and the results are shown in Fig. 8(e) and (f), respectively. The AWG

encoder/decoder can reach 15~20 dB PCR in most of the cases, while the PCR of the SSFBG is around 1 dB. That means the interference level ξ could be significantly reduced (up to 20 dB) using the AWG decoder with the same length of code. Therefore, this device has the potential to tolerate more active users at a high data rate without the need of optical threshold in an asynchronous OCDMA network [15].

b. Consideration of a cost-effective WDM/OCDMA

Figure 9 shows the architecture of the proposed 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 [14, 15] has very high 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 used as the low cost E/D. The hybrid of SSFBG and TVF-type E/D has already been verified for use as OC en/decoder [22]. Here we further used multi-port E/D as encoder and tunable TVF-type E/D as decoder to verify that this hybrid can work properly as well. Figure 10 (a) shows the waveforms of a generated 16-chip, 200Gchip/s OCs from the 16×16 multi-port E/D (upper) and TVF-type E/D (lower). The phase pattern of the represented OC is shown on the top of the figure. The auto-/cross-correlations of the hybrid of the multi-port encoder/tunable TVF decoder (hybrid E/D) are shown in Fig 10(b). The measured PCRs are shown in Fig. 6(c) together with those of a multi-ports E/D for four different OCs. They are in good agreement with each other, and the values range 12~22 dB, which is one key to enable multi-user asynchronous OCDMA by suppressing the noises.

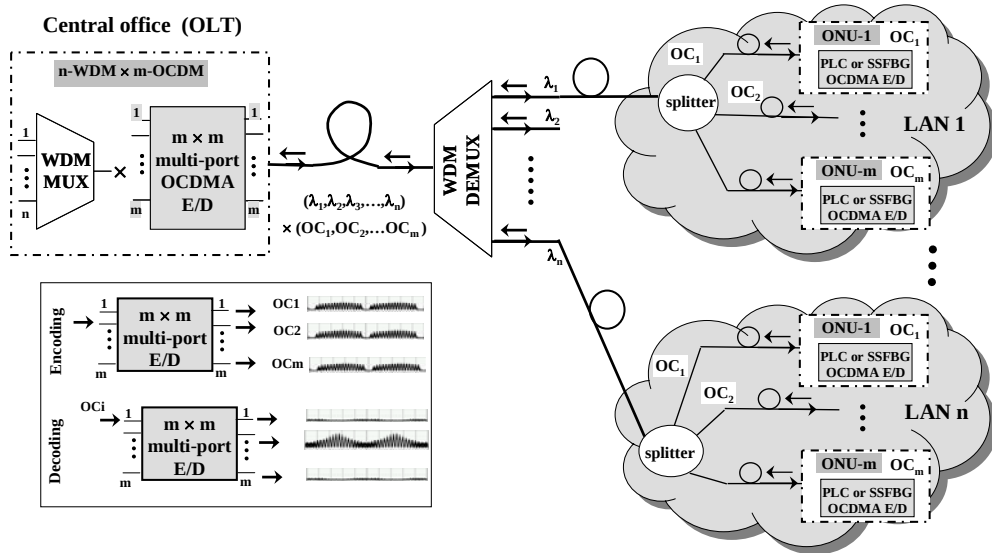


Fig. 9. Proposed WDM/OCDMA network architecture

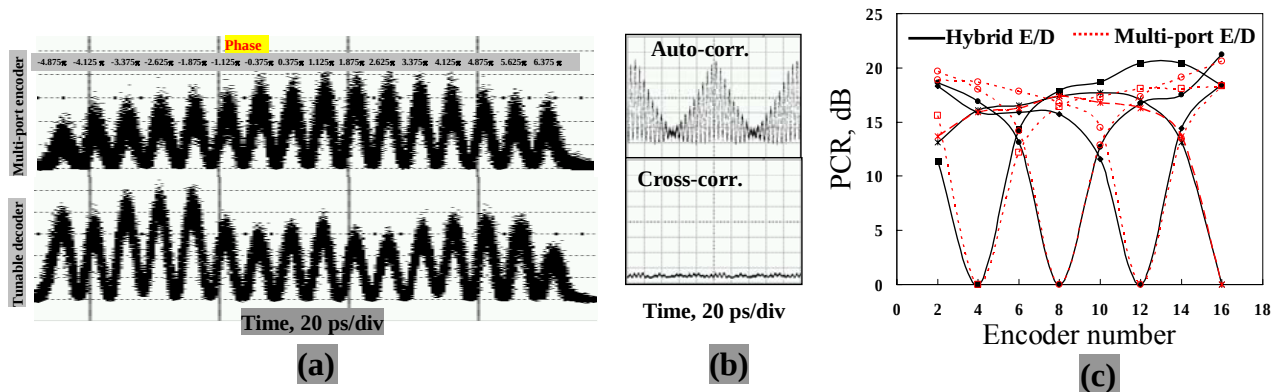


Fig. 10. Performance of multi-port encoder with TVF decoder

On the other hand, OCDMA using differential phase shift keying (DPSK) data format and balanced detection [6] will be another key to enable multi-user asynchronous OCDMA at 10Gbps without optical thresholder (OT) and forward error correction (FEC) due to its superior noise tolerance over conventional OCDMA using on off keying data format (OOK). Figure 11 shows the numerical results for the comparison of ODPSK- and OOK-OCDMA using the models proposed in [3, 6]. Figure 11(a) shows the number of active users (K) that can be supported with $\text{BER} \leq 6 \times 10^{-5}$ vs. average interference level ζ , which is defined as the average cross- to auto-correlation ratio (in dB) [3]. The three curves from right to left are for DPSK-OCDMA, OOK-OCDMA with opt. thresholder (Th) and fixed Th , respectively. For a given value of K , the DPSK-OCDMA can tolerate about 4 dB higher ζ comparing to OOK-DPSK with Opt Th and 5~6 dB higher comparing to OOK-DPSK with fixed Th . This is a significant improvement for OCDMA because more active users could be accommodated with a shorter optical code length. For example, by using a 511-chip optical code ($\xi \approx -27.1\text{dB}$), about 6 active users ($K=6$) could be supported at this BER for OOK-OCDMA with fixed Th , $K=9$ for OOK-OCDMA with Opt Th , and $K=17$ for DPSK-OCDMA. Figure 11(b) shows K vs. ζ with $\text{BER} \leq 1 \times 10^{-9}$. From right to left, the thick curves are for DPSK-OCDMA and OOK-OCDMA w/o OT (with opt Th), respectively; while the thin curves are for OOK-OCDMA using ideal OT and an OT with 5dB OSNR improvement respectively. The performance improvement of using OT in OOK-OCDMA can be clearly seen and it is dependent on the OSNR improvement of OT in practical system. On the other hand, the performance of DPSK-OCDMA is close to OOK-OCDMA with OT. Therefore, DPSK-OCDMA is superior over the OOK-OCDMA with advantages of improved receiver sensitivity, better tolerance to beat noise and MAI noise without OT, and no need for dynamic Th level setting [6].

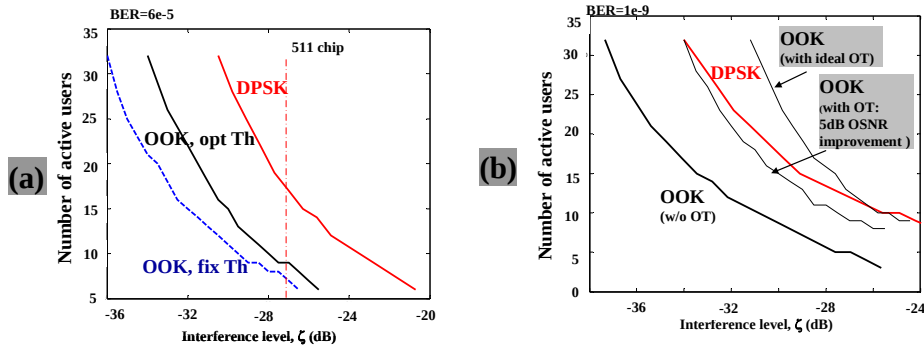


Fig 11 Performance comparisons between (a) DPSK- vs. OOK-OCDMA with fixed and optimal threshold ($\text{BER}=6\text{e}^{-5}$) (b) DPSK- vs. OOK-OCDMA with and w/o optical thresholder (OT) ($\text{BER}=1\text{e}^{-9}$)

c. Field trial of multi-user WDM/DPSK-OCDMA

Figure 12 shows the experimental setup of the field trial for multi-user WDM/DPSK-OCDMA. The field trial was done on an optical testbed of JGNII (Japan Gigabit Network II). JGN II is a nationwide open testbed network operated by NICT as a ultra-high-speed testbed networks for R&D collaboration between industry, academia, government. The fiber used in this experiment is installed in the field between our laboratory in Koganei city and Otemachi of downtown Tokyo in a loop-back configuration.

Three MLLD generated 3 WDM pulse signals with about 3.2 nm (400 GHz) channel spacing. The ~ 1.8 ps optical pulses were generated 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 $2^{31}-1$ pseudo random bit sequence (PRBS) from independent data sources. The signals were then multiplexed and sent to the port #1 of the 16 $\times$ 16 ports E/D. Inset α in Fig. 12 shows the spectrum of this multiplexed signal. 16 different OCs were generated at the 16 output ports, and then were mixed in an asynchronous manner with balanced power, random delay, random bit phase and random polarization states. Fixed fiber delay lines with incremental differences of 10 m were used in each branch to decorrelate the signals, variable optical attenuators (VOAs) were used to balance the power. Tunable optical delay lines were placed as well to investigate the system performance with different phases of signal-interference overlapping. In a practical PON environment, the polarization states of the signals may be random. However, for investigating the system performance in the worst scenario where the interference becomes most serious, polarization controllers (PCs) were placed to align the polarization states of all signals. Inset β in Fig. 12 shows the waveform of the mixed signals of 3 WDM, 12 OCDMA users. This signal was then launched into 100 km installed SMF. Three spans of

DCF with total dispersion of around 430, 860 and 430 ps/nm respectively have been used in the transmission line to compensate the dispersion.

After transmission, the WDM×OCDMA signal was first de-multiplexed by the WDM DEMUX with 400 GHz channel spacing, and later transmitted through a ~11km SMF before reaching the 16-chip programmable TVF-type decoder. The decoder was programmed to decode four different OCs correspond to those ones generated at the encoder ports 4, 8, 12, 16. A fiber-based interferometer and balanced detector perform the DPSK detection. The bandwidth of the receiver system is around 7.8 GHz to perform data-rate detection. Insets θ and ζ in Fig. 12 show the decoded signal and the electrical signal after the balanced detector respectively. The data was finally tested by the BER tester with clock signal obtained from the clock-data-recovery (CDR) circuit.

The measured BER performances are shown in Fig. 13. Figure 13(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 ($\text{BER} < 10^{-9}$) 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. Figure 13(b) shows a comparison of BERs between DPSK-OCDMA and OOK-OCDMA with and w/o FEC for $K=12$ [15]. The performance has been significantly improved in DPSK-OCDMA compared to OOK without FEC. Even compared to OOK with FEC, the sensitivity at $\text{BER}=10^{-9}$ was improved more than 2 dB. These results verify previous statement that DPSK-OCDMA can accommodate more active users than OOK-OCDMA without using FEC and OT. Figure 13(c) shows the BER performance degradation after field transmission. For $K=12$, error floor around 10^{-9} has been observed in several cases due to impairments during the 111 km transmission and non-uniformity of the PCR [14,

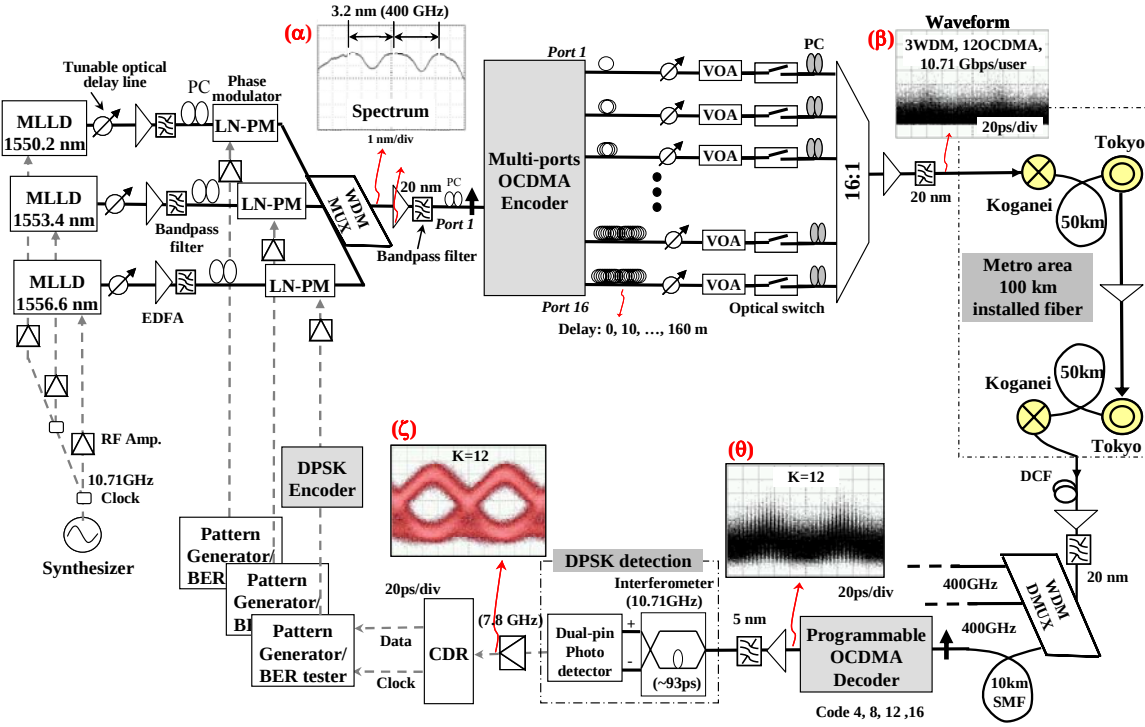


Fig. 12 Experimental setup of the multi-user WDM/DPSK-OCDMA field trial

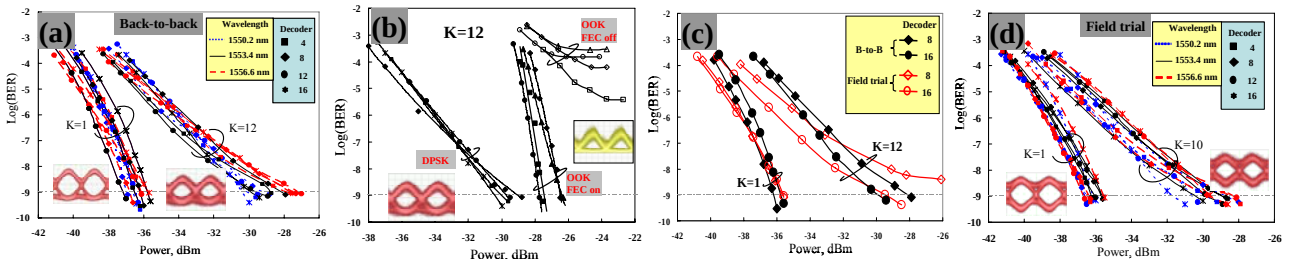


Fig. 13. BER performances

15]. Figure 13(d) shows that error free transmission has been successfully achieved for all the 4 decoders with 3-WDM and up to 10 OCDMA users in the field trial.

All the measurements were taken under the worst-case scenario by adjusting the tunable optical delay lines and PCs to guarantee the asynchronous operation. The threshold level was fixed to 0 in the measurement independent of K. Therefore, dynamic threshold level setting requirement could be relaxed in the receiver as well. The 4 ports were randomly chosen for good representativeness for all the others. The multi-user performances of other ports were tested to be within the spread of the shown results. The spectral efficiency (η) is about 0.32 and 0.27 bit/s/Hz for B-to-B and field transmission, respectively.

The capacity and spectral efficiency can be further enhanced by using larger scale multi-port encoder/decoder and FEC. Recently, Terabit payload capacity (1.24 Tb/s) asynchronous WDM/DPSK-OCDMA transmission field trial has been successfully demonstrated with a large scale (50×50 ports, 500 Gchip/s) multi-port encoder/decoder and FEC. The multi-port encoder/decoder was used in a novel multi-dimensional configuration to best fit the WDM/OCDMA system. Payloads of 5 wavelengths (600GHz spacing)×25-OCDMA users at 9.95328 Gbps/user have been successfully transmitted over 100 km field fiber in Tokyo with bit-error-rate (BER)<10⁻⁹ and spectral efficiency (SE) of ~0.41 bit/s/Hz for payload.

The 50×50 port encoder/decoder that can generate 50 coherent time-spreading OCs with 50 chips and 500 Gchip/s for this application was fabricated by NEL. Figure 14(a) shows its photo, basic configuration, and waveform of generated 50-chip, 50-level phase shift OC. In order to maximize the spectral efficiency of the system, it is essential to suppress the inter-channel cross talk to enable the WDM channel spacing close to the free-spectral-range (FSR) of the encoder/decoder. A multi-dimensional configuration was employed as shown in Fig. 14(b) in the experiment to minimize the WDM cross-talk, where, signals from different WDM channels go into different input ports of the encoder; therefore the multi-port encoder functions as both WDM multiplexer and OCDMA encoder simultaneously.

In the B-to-B experiment with FEC, error free (<10⁻¹²) has been achieved for all 25 OCDMA users in all 5 WDM channels. After field transmission, most of the users have also achieved error free except 3 users in λ_1 . These three users appeared BER floor at ~10⁻¹⁰. Compared to B-to-B case, the power penalty after field transmission is about 1.6 dB in average. The spectral efficiency (for payload) is 0.41 bit/s/Hz, that is a record value in asynchronous OCDMA.

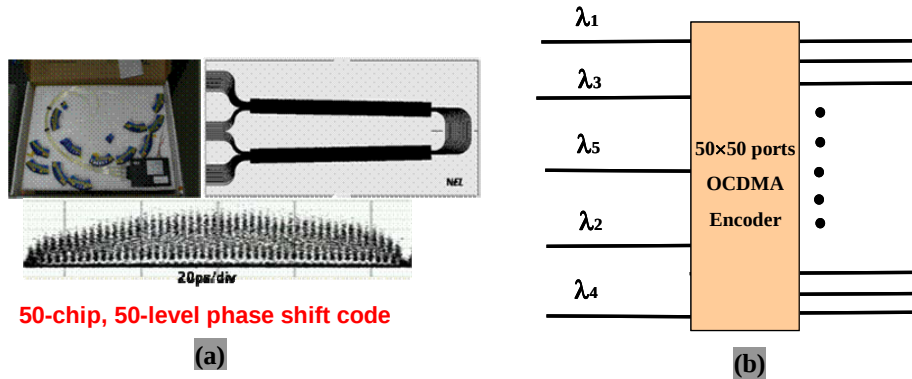


Fig. 14 (a) 50×50 ports multi-port encoder/decoder and (b) multi-dimensional configuration

d. Spectral efficiency enhancement by multilevel modulation formats

The spectral efficiency could be further enhanced by using multilevel modulation formats, including phase shift key or code shift key, to carry multi bit information with one pulse. Figure 15(a) shows the experimental setup of an OCDMA system using differential quaternary phase shift key (DQPSK) and FEC [21]. Four 8-chip, 10 GHz/chip micro-ring resonator (MRR) based encoder/decoders with four different Hadamard codes were employed in the experiment to generate four OCDMA signals. The four 10 Gb/s OCDMA signals were multiplexed synchronously to avoid beat noise and were further multiplexed in two polarization states to double the capacity. At the receiver, optical time gating was used after the MRR decoder to eliminate the MAI noise and a pair of DPSK demodulators were used to demodulate the I/Q signals. With the assist of FEC, error free has been achieved for 8 users within 80 GHz spectral range, resulting spectral efficiency of 0.87 bit/s/Hz.

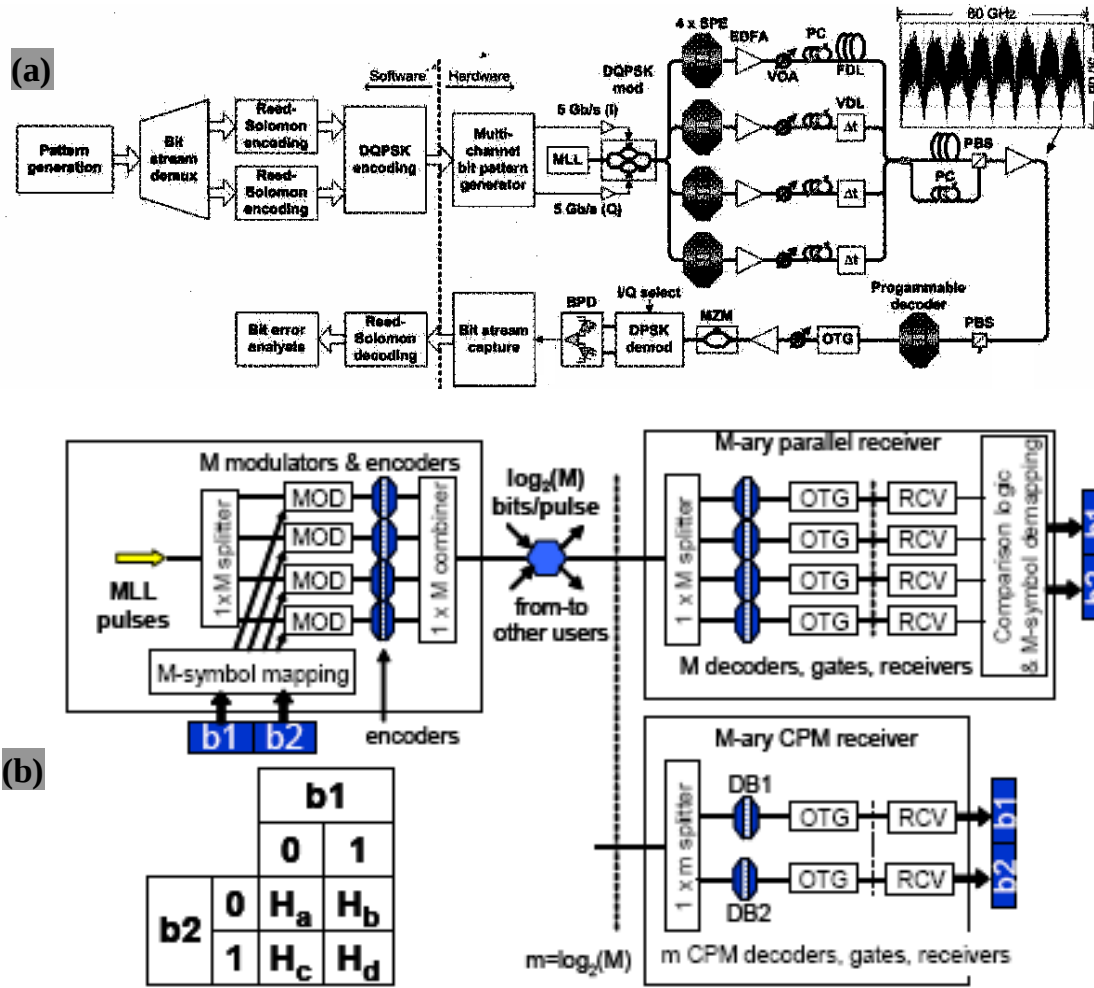


Fig. 15 (a) DQPSK-OCDMA experiment [21], (b) M-ary CSK OCDMA [23]

The multi-bit/symbol modulation could also be done with code shift key (CSK) [22-25]. Besides the enhanced spectral efficiency, the M-ary CSK OCDMA could also significantly enhance the security of the system. Figure 15 (b) shows one implementation of M-ary CSK OCDMA to carry $\log_2(M)$ bits/symbol using M OCDMA encoders [23]. Quaternary CSK (2 bits/symbol) has been demonstrated at 2.5 Gb/s. Recently, using another implementation method, a 16-ary (4 bits/symbol) CSK OCDMA has been demonstrated at 622 Mb/s [25].

IV. CONCLUSIONS

The rapid traffic growth demands large uplink bandwidth as well as downlink in the access network. WDM/OCDMA PON provides one promising solution to the symmetric high capacity access network with high spectral efficiency, cost effective, good flexibility and enhanced security. In a cost-effective WDM/OCDMA network, a large scale multi-port encoder/decoder can be employed in the central office, and a low cost encoder/decoder will be used in optical network unit (ONU).

The WDM/OCDMA systems have been experimentally demonstrated using SSFBG and multi-port OCDMA en/decoders. The SSFBG can serve as OCDMA encoder/decoder as well as WDM de-multiplexer that simplify the network architecture and make it more cost effective. 16-user OCDMA over 3-WDM with 100-GHz spacing has been experimentally demonstrated with single light source, 511-chip, 640 Gchip/s SSFBGs en/decoder.

The multi-port encoder/decoder enables high capacity, spectral efficient WDM/OCDMA. The field trial of a cost-effective asynchronous WDM/DPSK-OCDMA using hybrid E/D has been successfully demonstrated with frequency

efficiency of 0.27 bit/s/Hz in asynchronous environment. The total capacity is 3-WDM×10-OCDMA×10.71Gbps and transmission distance is 111 km. Using a 50×50 mutiport encoder/decoder in a novel multiple dimensional configuration and FEC, the total throughput has reached above Tera-bit/s (5 WDM×25-OCDMA×10 Gbps) with spectral efficiency of about 0.41. Using multi-level modulation formats to carry multi-bit information with single pulse, the total capacity and spectral efficiency could be further enhanced as well as the security.

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