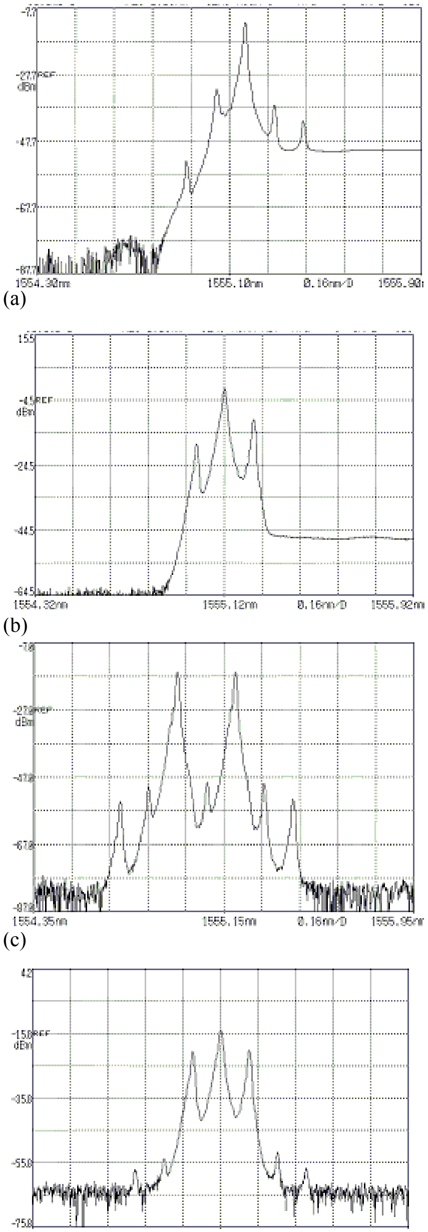
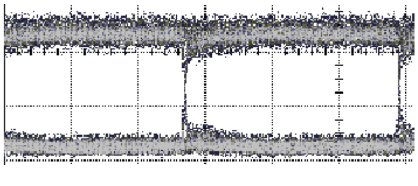
mission and extraction are given in Fig. 4. The BER curves in Fig. 5 show that the penalties induced by the labeling and transmission are about 0.3dB for both the label and payload.

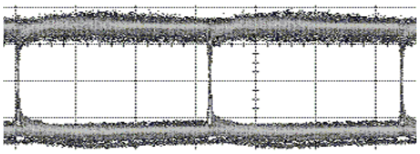


(d)

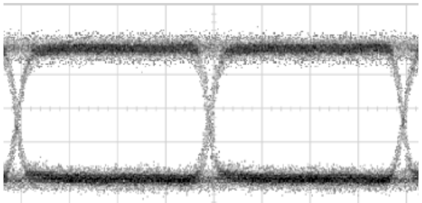
Fig. 3. Spectra of (a) the generated label with the suppressed carrier (b) the generated signal consisting of payload and label (c) the extracted label after first OADM (d) the payload with the residual label after second OADM.



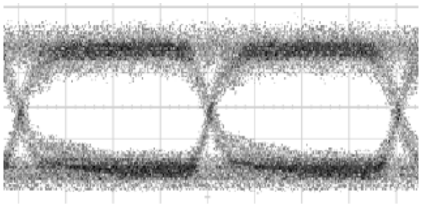
(a) 2ns/div



(b) 2ns/div



(c) 25ps/div



(d) 25ps/div

Fig. 4. Eye-diagrams of (a) original label before multiplexing (b) extracted label (c) original payload before multiplexing (d) extracted payload.

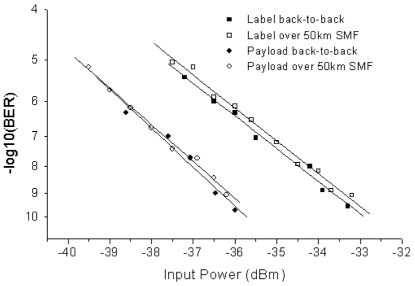


Fig. 5. Measured BER curves

4. Conclusions

We have proposed and demonstrated a novel method to generate an optically labeled signal by using the carrier suppression technique. The generated signal consists of a 10Gb/s payload and a 156Mb/s label, and shows good performance in a 50km transmission link.

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FD6 **9:30 AM**

All-Optical Wavelength and Time 2-D Code Converter for Dynamically-Reconfigurable O-CDMA Networks Using a PPLN Waveguide

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We demonstrate all-optical wavelength and time code conversion for O-CDMA networks at 2.5-Gbit/s with 10-Gchip/s. Difference-frequency generation provides wavelength-shifting and fiber-Bragg gratings introduce cyclic time-shifts to the incoming code, generating a new time/wavelength code with less than 0.7-dB power penalty.

1. 2-D OCDMA networks utilizing code-converters

There has recently been much renewed interest in optical code-division-multiple-access (O-CDMA) due to its potential for enhanced data security and spectral efficiency, especially when considering the fine granularity of traffic in local-area-networks (LANs) [i,ii]. However, a key drawback for O-CDMA has been the necessity of generating, propagating, and detecting extremely short chip times (i.e the time- domain subdivisions of a bit) such that there are sufficient orthogonal codes [iii]. One approach for alleviating the small chip time has been the introduction of a two-dimensional O-CDMA architecture, in which each bit is subdivided into a combination of chip times and a discrete set of wavelengths [iv, v]. Even with a time/wavelength approach, a reasonable number of wavelengths and chip times cannot accommodate many simultaneous users. Therefore, it may be of great value for an O-CDMA network to **re-use** a finite set of 2-D codes across different parts of the network. Moreover, such code re-use, which is analogous to wavelength re-use in a WDM network, should be reconfigurable in order to account for changing traffic patterns and to alleviate congestion.

In general, a 2-D code converter would need to redistribute the optical energy in both dimensions, namely, the chip times and the wavelengths. A brute-force electronic approach for code conversion would be to decode the O-CDMA signal using autocorrelation and threshold detection, change the code in the electronic domain, and then re-encode the data on an optical signal [vi]. A potentially more rapid, efficient and transparent approach for high-data-rate signals is to perform the code conversion in the optical domain.

Although there were generic demonstrations of all-optical wavelength conversion for wavelength routing in WDM networks and separate demonstrations of all-optical time shifting for time slot routing in TDM networks [vii], there has been no reported demonstration of an all-optical O-CDMA 2-D code converter.

We demonstrate all-optical, wavelength and time, code conversion for OCDMA networks at a user data rate of 2.5 Gbit/s with 4 chips/bit and 2 wavelengths/code. Difference frequency generation (DFG) in a periodically-poled lithium-niobate (PPLN) waveguide enables wavelength conversion [viii] and fiber Bragg gratings (FBGs) are used to provide cyclic time shifts [vii] to the incoming code to generate a new time/wavelength code. We also demonstrate switching of input frames to code-converted frames to resolve code contention between 2 LANs sharing the same particular code. Our technique for code conversion introduces less than 0.7 dB power penalty.

2. Time/wavelength O-CDMA structure and code conversion

Figure 1 explains the structure of a time/wavelength 2-D O-CDMA code conversion. Interconnectivity between multiple O-CDMA LANs can be made efficient by incorporating code re-use. To provide this functionality, a code converter acts as a bridge between two LANs. If a node in LAN-A needs to communicate with another node in LAN-B using code-1, the network must ensure that code-1 is not already being used in LAN B. If code-1 is being used in LAN-B, the network can select another code common to both the LANs. This, however, requires a large number of orthogonal codes to provide adequate networking. A potentially better alternative is to employ a code converter that takes frames containing code-1 from LAN-A and changes the data to a new time/wavelength code that is currently not being used in LAN-B.

The code conversion process is carried out in two parts. First, the incoming set of wavelengths is mapped onto a new set of wavelengths by DFG in a PPLN waveguide. Figure 2a shows the spectrum of the signal at the PPLN output with all input wavelengths mapped onto the mirror images of themselves with respect to the pump. The device employs a $\chi^{(2)} : \chi^{(2)}$ nonlinear process to shift data to new wavelengths at $\lambda^c \approx 2\lambda_{pump} - \lambda_{signal}$. DFG is an instantaneous process with a wide operational bandwidth of ~ 50 nm. Moreover, the PPLN has negligible spontaneous emission noise and no intrinsic chirp. [viii]

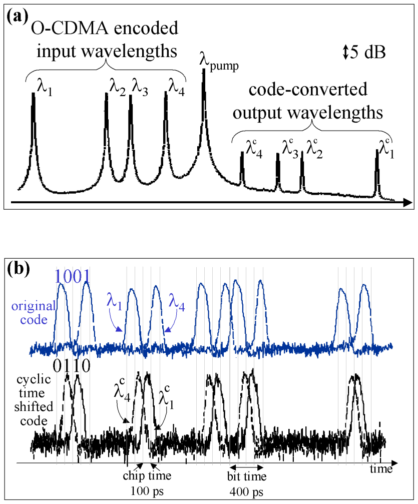

Figure 2. (a) Wavelength shifting using a PPLN waveguide. (b) Time shifting of the 2-D code converter.

The second step provides code conversion in the time dimension through wavelength dependent delays (FBGs). The FBGs are tuned to the output wavelengths of the PPLN waveguide for the particular code to be converted, λ^c_1 and λ^c_4. They are separated by a distance of 4 cm which produces a cyclic shift of 4 chip times for the reflected wavelengths. This causes the pulses of the output wavelengths, λ^c_1 and λ^c_4, to change position with respect to one another, as shown in Figure 2b. Thus, the data leaving the code converter is coded with a new set of wavelengths and cyclically shifted time chips (1001 : 0110) compared to the original code.

3. Experimental Setup

Our experimental setup is shown in Figure 3. To encode the data, four lasers are modulated with the same pulse pattern and the introduction of 1-bit delay between the individual wavelengths produces the chips for each code. The original code has of the chip pattern C_1='1001' for "1" data bits with the first time chip at λ_1 = 1539.04 nm and the fourth at λ_4 = 1547.68 nm. To represent other codes (C_2='1100' and C_3='1010') propagating alongside our target code in the network, pulses at λ_3 = 1545.29 nm and λ_2 = 1543.56 nm occupying the third and second time chips of each bit, respectively. Since the module operates at a user data rate of 2.5 Gbit/s, each bit is split into four chip times, and the modulator operates at 10 Gbit/s. The pulse waveforms of code C_1 are shown in Figure 2b.

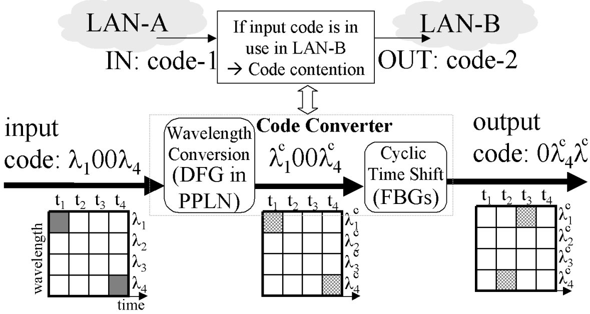

Figure 1. Concept of the 2-D O-CDMA code converter to resolve code contention for 2 LANs sharing the same particular code.

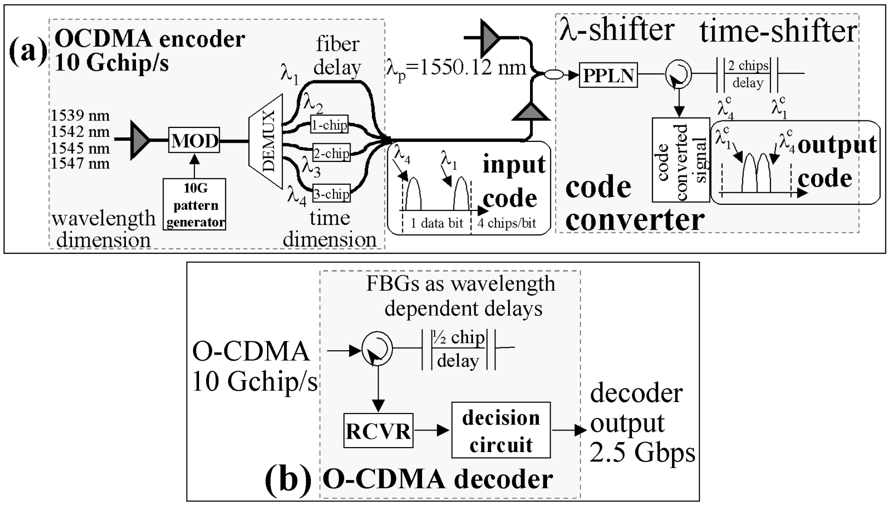

Figure 3. (a) O-CDMA encoder with 4 wavelengths and 4 time chips and the 2-D code converter with wavelength and time shifting. (b) O-CDMA decoder composed of the autocorrelation and threshold detection circuit.

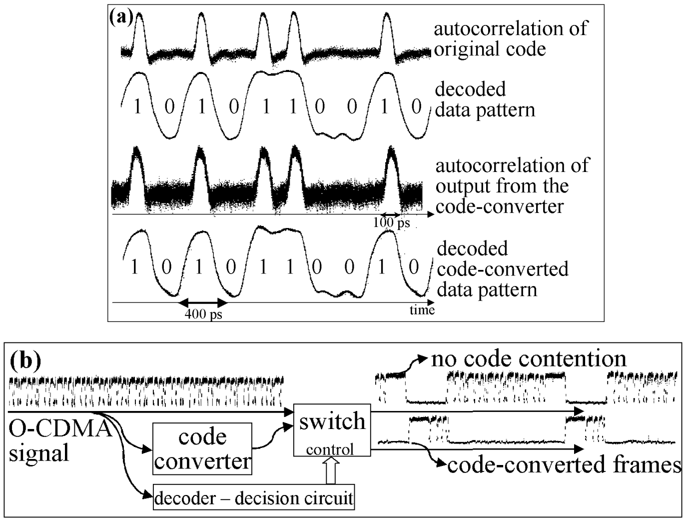

Figure 4. (a) Decoding of the input and code-converted codes in the system. (b) Code contention resolution at a routing switch using the code converter module. Whenever a LAN-frame is coded with a code in use in LAN-B, the code-converted signal is routed at the switch output.

The amplified and ASE filtered O-CDMA signal and the pump are coupled into the PPLN waveguide. All four incoming wavelengths are mapped onto their DFG counterparts. The time-shifter (FBGs) is tuned to two of the new wavelengths, namely λ^c_1 = 1561.60 nm and λ^c_4 = 1552.72. These wavelengths correspond to the first and last pulses in the original code, C_1. The first FBG encountered is tuned to reflect the wavelength (1552.72 nm) of the last chip in the bit and the second FBG to the wavelength (1561.60 nm) of the first chip in the bit. Since the FBGs are separated by two bit times, the total delay will be of 4-bit duration, and the output from the circulator will contain adjacent pulses at 1552.72 nm and 1561.60 nm, but with their order reversed. The correspondence between the old and new code is depicted in Figure 2b.

To decode the data we employ an optical threshold technique using an optical power adder. Two FBGs are separated by a distance equivalent to half of the time between the two pulses forming the code. Reflection from these gratings causes a time shift between the chips, which results in the pulses adding up and generating a correlation peak whenever there is a "1" bit in the input data stream. An electronic threshold circuit converts this output signal to the decoded data stream. The correlation peaks and the matching decoded signals are shown in Figure 4a for the input O-CDMA signal and the code-converted output signal. The noise in the decoder input for the code-converted signal resulted from EDFA ASE noise. We also demonstrate switching of optical packets based on whether a particular code is present in the data frame. LAN-frames of 16 bytes each are encoded into O-CDMA codes with some frames containing the original code. We assume that our original code is in use in LAN-B and therefore will cause contention. A set of decoder gratings is used to detect the presence of the original code and to generate a switching signal, which is used to control a lithium-niobate electro-optic switch to route the code-converted signal in the case of code contention. Figure 4b shows the pulse waveforms and the switch setup for the routing portion of our demonstration.

4. Results and Discussion

2-D O-CDMA code conversion was performed successfully using wavelength conversion and cyclic time shifting.

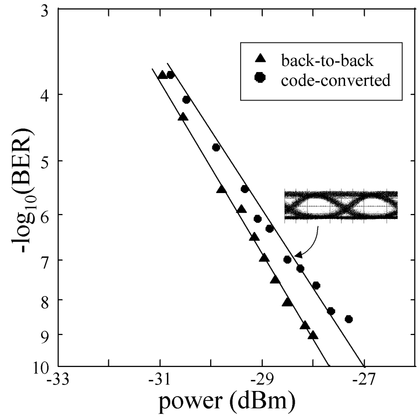

Figure 5. BER measurements of our module.

BER measurements (Figure 5) taken on the code-converted 10 Gchip/s bit streams show that our technique of code conversion introduces less than 0.7 dB power penalty.

Our technique for code conversion is capable of accommodating several codes. The PPLN has an operational bandwidth ~50 nm, which may accommodate up to 20 wavelengths with ~0.8 nm separation. O-CDMA encoding based on multiple wavelengths per chip time increases the number of available codes and improves their cross-correlation characteristics resulting in lower crosstalk. Sampled FBGs can be used to reflect more than one wavelength simultaneously, thereby allowing detection of multiple wavelengths in a single chip time. However, the grating length grows with the number of wavelengths to be detected in a single chip time. This places a constraint on the spacing between two gratings if the chip rate is higher than 10 Gchip/s.

5. References

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FE 8:00 AM - 10:00 AM

B401-B402

Transmission Impairments

Noboru Edagawa, *KDDI R&D Laboratories, Inc., Japan, Presider*

FE1 (Invited) 8:00 AM

Tradeoffs for Performance in Long-Haul Transmission Systems: A Carrier's Perspective

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Tradeoffs abound in optical transmission system design, and it's critical for carriers to understand their priorities based on network/service characteristics, and select systems that meet their needs at the lowest first and per-channel cost.

Now more than ever, it is important for a carrier to have a good view of their network and its needs prior to launching into the search for a new long-haul transmission system. There are a number of tradeoffs that can be made in system design, and having a clear view of network topology, traffic requirements and operational needs can help in finding the best system for a particular carrier's network and application. There is no "one size fits all" system, and each one has been designed with a particular set of costs and capabilities in mind.

Of course, lowering costs are foremost in every carrier's mind today when it comes to long-haul transmission systems. A few years ago, the conventional wisdom was to lower costs by putting more and more bandwidth on a fiber, sharing common equipment over more channels and driving down per-wavelength dollars. Today, first wavelength costs are equally important in laying new systems, making sure that cost saving are realized within an achievable time window. Often, achieving the optimum fully-loaded wavelength cost can lead to prohibitive first wavelength costs, and vice-a-versa. Operational costs also play a harder-to-quantify but important role when evaluating system options, and operational savings mechanisms such as power and footprint are considered up-front in decision-making.

There are a few network characteristics that are key to setting requirements on a long-haul transmission system:

1) The amount of available fiber, and the fiber type and characteristics

2) The network topology, including distance required between add-drops, service needs at add-drops and number of on/off ramps on a system

3) The service topology, including average distance of wavelengths between customers or grooming points in the network

4) The level of flexibility required of the system, including granularity of add/drops, the need for network reconfiguration at a wavelength level, the need to support a variety of rates and services

5) The amount of automation required of the system, including seamless system turn-up, fault location to a root cause, and wavelength provisioning.

Fiber remains an important driver for system design. For carriers that have a lot of fiber available, heroics to pack large number of channels on a single set of equipment can add unnecessary cost. For newer fibers, the need for mitigation of PMD or fine-tuning of Chromatic Dispersion may also prove an unneeded expense. However, to support a wide variety of fiber types, including older fiber types such as True-Wave Classic with high variation in Chromatic Dispersion and older SSMF fiber with PMD issues, techniques that may add cost but allow longer distances without regeneration may prove in. For some system suppliers, having a variety of transponders that include low-cost options for better fiber and/or shorter distances, and higher-cost options that can give increased distance or support older fiber is one way to meet the both types of carrier requirements. Supporting, testing and manufacturing multiple codes of transponders, however, can add cost as well, and may dwarf the benefits of the lower technology expense.

Network topology drives a number of other factors that can add cost to a system. Understanding the number of cities that need to be connected, and the volume of traffic that is required at each city will drive the add/drop design. Banded designs can sometimes save money over per-channel routing, however the size of the bands and the flexibility to re-use capacity may limit the application for a banded system. Understanding if the network design is hubbed, and all OADM traffic will be expressed to the nearest end-terminal, or if the design is meshed and requires full connectivity between all cities will drive the tolerance for banding and help determine the size of the bands that are needed. While the first cost of a banded system may prove in, for meshed traffic the system may exhaust before a similar per-channel OADM system would.

Service topology is also important. Designing a network of 3000 km systems when a significant portion of the wavelengths are dropped or groomed after 500 km, may or may not make sense. While the economics may look attractive compared to shorter back-to-back systems, the savings may not begin to cover the costs of installing, testing and maintaining such long optical chains over time. Having a strategy to grow a system from a shorter length to a longer length with more OADMs allows the network to evolve along with the services, as wavelength and data services grow to require longer ungroomed distances.

Flexibility is an important tradeoff as well. Without a crystal ball, carriers are trying to put in systems that can evolve as the traffic needs evolve. The ability to easily change from an amplifier to an OADM if a traffic need emerges and the ability to grow traffic at an existing OADM without the need to touch the system by adding equipment or cabling at intermediate sites can all drive more acceptable cost into a system. Static systems that do not allow reconfiguration require a carrier to have a good view of network growth over years. In these turbulent times for telecommunication, every carrier would like the ability to grow and evolve their networks as the service needs materialize, without locking that growth in on day one.

Finally, automation can both drive cost into a system and drive operational expense out of a network. Each carrier has a "level of pain" that they are willing to go through to turn a system up, to maintain a system in the field, and to provision new wavelengths. By automating those functions through system design, the need for expensive human intervention can be minimized throughout the lifetime of a system. These improvements are always difficult to quantify in terms of operational dollars, but every carrier realizes them as differentiators that become more and more important as these transmission systems become more and more complex.

All systems designers are faced with tradeoffs when they engineer their systems, and having a clear view of who you are designing your system for can help you to better understand their needs. Are you designing your system for a greenfield carrier or an enterprise application where the distances between on/off ramps is long and the traffic is mostly hubbed into a few major cities? Or for a customer with a large footprint that needs high connectivity between large cities and an ability to pick up traffic at a number of intermediate ones? Having in mind the customer requirements up front will help in deciding the optical requirements for channel count, system reach and tolerance to fiber variations for the design. Just designing a system for the highest bandwidth at the longest reach no longer makes sense in this economy, as carriers become more focussed on the bottom line and less and less focussed on nifty technology.