# A Multirate Upgradeable 1.6-Tb/s Hierarchical OADM Network

Yikai Su, *Member, IEEE*, S. Chandrasekhar, *Fellow, IEEE*, Roland Ryf, *Member, IEEE*, C. R. Doerr, *Member, IEEE*, Lothar Möller, Indra Widjaja, *Senior Member, IEEE*, Greg Raybon, *Member, IEEE*, David T. Neilson, *Senior Member, IEEE*, Tao Zhou, Lawrence Buhl, and Stojan Radic, *Member, IEEE*

***Abstract*—We report a hierarchical optical add–drop multiplexer (OADM) network that supports 10-, 40-, and 160-Gb/s data rates with the same bandwidth efficiency. The data rates can be upgraded without hardware modification in the OADM. This hierarchical OADM network is equipped with high capacity (1.6 Tb/s) for traffic growth, while providing different granularities for diverse bandwidth requirements as fine as 12.5 GHz in optical domain. We investigate the transmission penalty through the waveband OADMs, and compare the performance between all-through traffic and add–drop traffic of neighboring wavebands at 40-Gb/s rate.**

***Index Terms*—Filter distortion, hierarchical systems, networks, optical communication.**

## I. Introduction

IN DESIGN and implementation of optical transparent networks, efficient utilization of bandwidth becomes challenging due to traffic demands with different end-to-end bandwidth requirements and data rates that are likely to change as the offered services evolve. Current optical networks are designed with fixed channel bandwidth, which would result in either low bandwidth-utilization efficiency for low data-rate traffic, or difficulty in upgrading to higher data rates since the wavelength multiplexer–demultiplexers have to be replaced. A variable-bandwidth optical add–drop multiplexer (OADM) is desired to satisfy diverse customer requirements, reduce cost in data rate upgrade, and enable high-bandwidth efficiency at various data rates.

In this letter, we present a variable OADM that supports 10-, 40-, and 160-Gb/s data rates with the same spectral efficiency of 0.4 b/s/Hz. One main feature is that the data rate can be smoothly upgraded without replacing any hardware in the OADM node. This is achieved by combining neighboring channel bandwidths to form a wider bandwidth with a fine granularity of 12.5 GHz in optical domain. Fig. 1(a) shows the concept of such a variable-bandwidth OADM based on dynamic blocker filters. However, the fine granularity increases the number of control elements and, therefore, complicates the network control and management. For example, to cover the $C$-band of 4 THz with 12.5-GHz granularity, 320 elements are needed. TSuch a device is notavailable yet even at the research stage. To reduce the device and control complexity, bundling of wavelengths along the same paths in a network and optical bypassing of through traffic is an effective approach to reducing the node complexity, considering that most traffic in a network node is through traffic (typically $\sim$75%) [1]. The concept of multistage switching at wavelength and waveband levels has been introduced to reduce the number of connection ports in the nodes [1]–[4]. In Fig. 1(b), we present a new hierarchical OADM consisting of waveband and wavelength levels based on a parallel architecture that does not require space switch fabrics as seen in [2], [3], thus, saving the number of connection ports in the node and the associated control. We investigate the transmission of 40 $\times$ 40 Gb/s signals through multihop hierarchical OADMs and compare the performance between all-though traffic and add–drop traffic of neighboring wavebands.

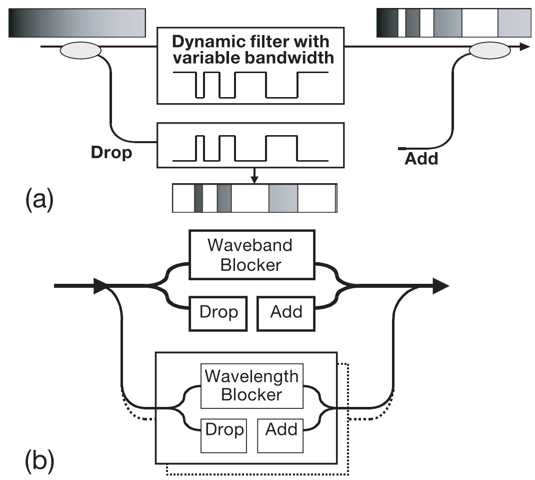


Fig. 1. (a) Illustration of the variable-bandwidth OADM at the wavelength level. (b) Hierarchical OADM consisting of wavelength and waveband levels to reduce the control complexity.

## II. OADM Architecture and Features

Fig. 1(b) shows the hierarchical OADM node architecture. The node has two layers in parallel that consist of waveband and wavelength levels, each providing different granularities. Incoming signals are power-split and fed into the waveband

Manuscript received June 20, 2003; revised September 3, 2003. This work was performed while Y. Su was with Bell Laboratories, Holmdel, NJ.

Y. Su was with Bell Laboratories, Lucent Technologies, Holmdel, NJ 07733 USA (e-mail: yikaisu@ieee.org) and is now with Shanghai Jiao Tong University, Shanghai 200030, China.

S. Chandrasekhar, R. Ryf, C. R. Doerr, L. Moeller, I Widjaja, G. Raybon, D. T. Neilson, and L. Buhl are with Bell Laboratories, Lucent Technologies, Holmdel, NJ 07733 USA (e-mail: yikaisu@ieee.org).

T. Zhou is with Princeton University, Princeton, NJ 08544 USA.

S. Radic is with the University of San Diego, La Jolla, CA 92093 USA.

Digital Object Identifier 10.1109/LPT.2003.820495

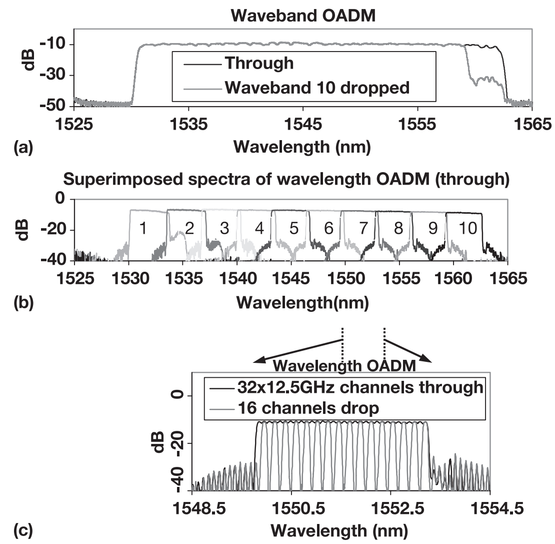


Fig. 2. (a) Waveband OADM transmission characteristic. (b) Wavelength OADM transmission characteristic for all channels through. Spectra are superimposed to show that the wavelength OADM can be shifted to any waveband. (c) Transmission characteristic of the wavelength OADM (set in Waveband 7) at through and odd-channel drop conditions, respectively.

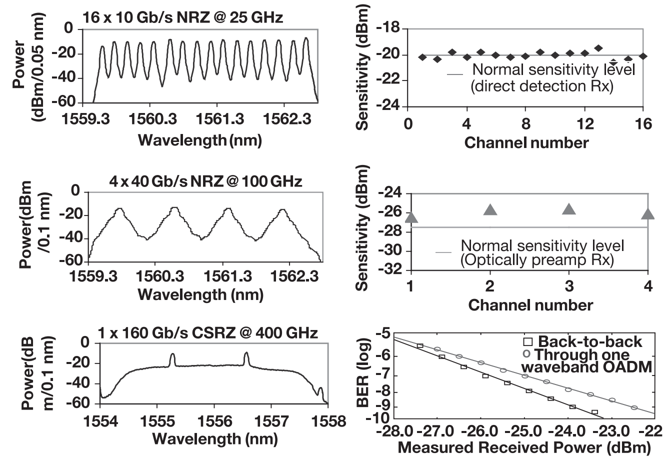


Fig. 3. Optical spectra of 10-, 40-, and 160-Gb/s signals of $2^{31}-1$ and their corresponding receiver sensitivity measurements through the OADM node.

and wavelength OADMs, each operating in a broadcast and select manner similar to that in [5] based on blocker filters. The wavelength OADM provides variable bandwidths as fine as 12.5 GHz, and as coarse as 400 GHz, which is the total available bandwidth of the wavelength OADM. We define a waveband to have 400-GHz bandwidth. Once bundled traffic streams fill 400 GHz, they are then passed through the waveband OADM. The coarse granularity in the waveband OADM helps to reduce the number of connection and control ports, and therefore, the node complexity that is seen in the wavelength OADM, while the wavelength OADM provides flexible bandwidths with fine granularity. Unlike the $N \times N$ wavelength selective-type switch fabric as in multigranularity optical cross-connect [2], the parallel architecture is based on blocker-type filters for the wavelength and waveband OADMs. Therefore, no space switch fabric is needed at the waveband–wavelength level. In addition, the parallel structure also reduces the signal degradation due to the cascading of filters. Depending on the traffic pattern as well as wavelength assignment algorithm used, there could be one or more wavelength OADMs attached with a waveband OADM. The waveband and wavelength OADMs should coordinate with each other; i.e., if a given wavelength is to be dropped through a wavelength OADM, the corresponding waveband in the waveband OADM should be blocked.

The waveband OADM used is a planar waveguide add–drop filter [6]. However, only input–output ports of the device are used so it behaves as a blocker filter. It covers 32 nm, which in our application is divided to ten wavebands each having 400-GHz bandwidth. Fig. 2(a) shows the filter shapes when the OADM is set to through state and one waveband (rightmost) is dropped, respectively. The limited extinction ratio of the waveband OADM would cause in-band crosstalk penalty when signals are dropped at a node and new signals are added in the same channels. However, the extinction ratio can be improved to $> 30$ dB, as shown in [6], if the unused optical ports of the device are carefully terminated to reduce reflection. The wavelength OADM is a blocker-type filter that supports different bandwidths. Previously, wavelength OADMs were demonstrated in long-haul networks at a fixed data rate of 10 Gb/s [4], [5]. Here, we show the variable-bandwidth OADM that supports multiple data rates of 10, 40, and 160 Gb/s, with the same spectral efficiency. This wavelength OADM is a microelectromechanical-system-based blocker filter with 32 continuous channels using a design similar to [7], and the channel spacing is designed to be 12.5 GHz. For the device used in the experiment, the insertion loss is $\sim$9 dB. In the worst case, the loss ripple is 1.2 dB, and the group delay ripple is 7 ps. The measured average dispersion over the passband is $< 1$ ps/nm, and the mean extinction ratio of the blocker is 35 dB. Any arbitrary number of neighboring channels can be combined to form a new wider wavelength channel to support higher data rates. Thus, data-rate upgrade can be realized without hardware modification in the OADM node. The wavelength OADM can be shifted to any waveband by simple mechanical adjustment, as shown in Fig. 2(b). Fig. 2(c) shows when the wavelength OADM is shifted to Waveband 7 the transmission characteristic of the filter for all through condition and 16 odd channels dropped, respectively, showing the 12.5-GHz optical bandwidth.

We investigate the performance of the OADM node in supporting multiple data rates. Since data traffic could pass through waveband OADMs, wavelength OADMs, or both types through multiple hops depending on the traffic demands, we cascade a waveband with a wavelength OADM and launch signals at different data rates to characterize the component performance. With the same spectral efficiency of 0.4 b/s/Hz, we send 16 $\times$ 10 Gb/s nonreturn-to-zero (NRZ) on 25 GHz, 4 $\times$ 40 Gb/s NRZ on 100 GHz, and 1 $\times$ 160 Gb/s carrier suppressed return-to-zero (CSRZ) [8] on 400-GHz grids through the cascaded waveband and wavelength OADMs to measure the penalties at a bit-error rate (BER) of $10^{-9}$. Fig. 3 summarizes the results. The receivers are equipped with tunable filters to select the channel to be measured. We observe no penalty for 10-Gb/s NRZ signals, $\sim$1.5-dB penalty for 40-Gb/s NRZ signal, and 1.5-dB penalty for 160-Gb/s CSRZ signal through one waveband OADM since the wavelength OADM is no longer needed

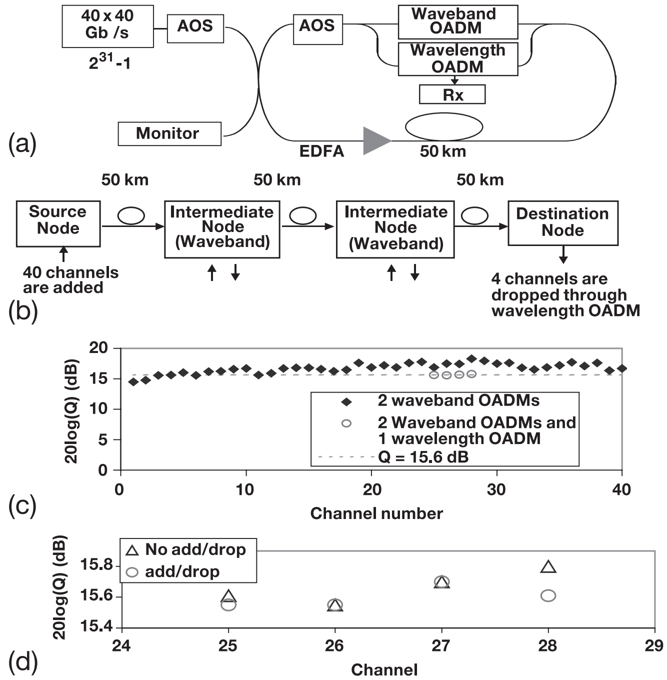


Fig. 4. (a) Recirculating loop setup to demonstrate multihop waveband and wavelength add–drop. AOS: acoustooptic switch. (b) Corresponding network scenario. (c) $Q$ measurements. (d) Comparison of all through traffic with add–drop of neighboring waveband signals.

for this case. The penalties can be primarily attributed to the loss and group delay ripple of the blocker filters. We have measured the receiver sensitivity with wider filter bandwidths, which do not improve the sensitivity performance. Note that when the data rate is upgraded from 40 to 160 Gb/s, the 160-Gb/s signal needs to be set on the ITU grid specified with 50-GHz spacing. In a study of a large mesh network [9], the average number of node hops is 3.24. In Section III, we investigate the transmission performance through three hops at 40-Gb/s rate.

## III. Optical Transport Performance

We perform an experimental investigation of multihop signal transmission through waveband and wavelength OADMs at 40-Gb/s rate. It can be reasonably assumed that the signals typically travel through multiple waveband OADMs before they are dropped through a wavelength OADM at the destination node. Here, we use a recirculating loop setup to study the cascading effects of filters; we also compare two network scenarios—all through traffic and add–drop of neighboring waveband traffic at each intermediate node. Note that in contrast to [4], there is no guard band between adjacent wavebands in our experiment.

Fig. 4(a) shows the simplified experimental setup. We focus on the network add–drop functions; therefore, no intention is placed to improve long-haul transmission performance. The loop consists of 50-km TW-RS fiber whose dispersion is 100% precompensated. The configuration can mimic the network scenario shown in Fig. 4(b), where 40 $\times$ 40 Gb/s NRZ signals are added at the source node, then the signals travel through two waveband OADMs (two loops), and finally four channels in Waveband 7 are dropped through a wavelength OADM at the destination node (third loop). Fig. 4(c) shows the $Q$ measurements of 40 channels after two intermediate nodes (the receiver is moved to waveband OADM in this case), and four channels that are dropped through the wavelength OADM. In this experiment, OSNR appears to be the main factor affecting the system performance in addition to the filter concatenation penalty, since the $Q$ values are coincident with OSNR measurements. The combined effects of OSNR degradation and filtering, as well as other impairments, are investigated in [10]. Nevertheless, the $Q$ values of Waveband-7 signals are above 15.55 dB or BER $\leq 10^{-9}$ after three-hop transmission. We also compare the performance of Waveband 7 in the case of all-through traffic and add–drop of neighboring Wavebands 6 and 8. At each intermediate node, Wavebands 6 and 8 are dropped and fresh signals are added in the same bands. Fig. 4(d) shows that there is no penalty for the central channels 26 and 27 in Waveband 7, while very little penalty is observed for the edge channels. Note the $Q$ values were obtained based on BER measurements over a long time period ($\sim$30 s), so that random deviations were removed.

## IV. Conclusion

We have demonstrated a novel OADM that supports multiple data rates of 10, 40, and 160 Gb/s with the same spectral efficiency. A key feature of this OADM is that data rate upgrade does not require replacing hardware in the OADM nodes. A 3-hop transport experiment is carried out with 40 $\times$ 40 Gb/s signals, with little penalty observed for a through waveband when neighboring wavebands are added and dropped at every node hop.

## References

[1] L. Noirie, M. Vigoureux, and E. Dotaro, "Impact of intermediate traffic grouping on the dimensioning of multi-granularity optical networks," in *Proc. OFC 2001*, Anaheim, CA, Paper TuG3.
[2] L. Noirie, C. Blaizot, and E. Dotaro, "Multi-granularity optical cross-connect," in *Proc. ECOC 2000*, Munich, Germany, Paper 9.2.4.
[3] A. A. M. Saleh and J. M. Simmons, "Architecture principles of optical regional and metropolitan access networks," *J. Lightwave Technol.*, vol. 17, pp. 2431–2448, Dec. 1999.
[4] D. Penninckx, G. Charlet, J.-C. Antona, and L. Noirie, "Experimental validation of a transparent waveband-based optical backbone network," in *Proc. ECOC 2002*, Copenhagen, Denmark, Paper 6.4.4.
[5] M. Vasilyev, I. Tomkos, J. Rhee, M. Mehendale, B. Hallock, B. Szalabofka, M. Williams, S. Tsuda, and M. Sharma, "Broadcast and select OADM in 80 × 10.7 Gb/s ultra-longhaul network," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 332–334, Feb. 2003.
[6] C. R. Doerr, L. W. Stulz, M. Cappuzzo, E. Laskowski, A. Paunescu, L. Gomez, J. V. . Gates, S. Shunk, and A. E. White, "40-wavelength add–drop filter," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1437–1439, Nov. 1999.
[7] D. T. Neilson, D. S. Greywall, S. Chandrasekhar, L. L. Buhl, H. Tang, L. Ko, N. R. Basavanhally, F. Pardo, D. A. Ramsey, J. D. Weld, Y. L. Low, J. Prebyla, R. Scotti, A. Gasparyan, M. Haueis, and S. Arney, "High-dynamic range channelized MEMS equalizing filter," in *Proc. OFC 2002*, Anaheim, CA, Paper ThCC3.
[8] L. Möller, Y. Su, X. Liu, J. Leuthold, and C. Xie, "Ultra high-speed optical phase correlated data signals," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 1597–1599, Nov. 2003.
[9] R. Lingampalli and P. Vengalam, "Effect of wavelength and waveband grooming on all-optical networks with single layer photonic switching," in *Proc. OFC 2002*, Anaheim, CA, Paper ThP4.
[10] Y. Su, G. Raybon, Z. Zheng, S. Chandrasekhar, R. Ryf, and L. Möller, "40-Gbit/s RZ-signal transmission in a transparent network based on wavelength-selective optical cross connect," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 1467–1469, Oct. 2003.