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効率的なグルーミング率制約を実現する 階層型光クロスコネクトノードアーキテクチャ

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あらまし 将来の爆発的なトラフィックの増加に備え，波長パスを論理的に束ねて波長群パスとし，一括中継処理を行う階層化光パスネットワークの研究が進められている．階層化光パスネットワークを構成するノード(階層型光クロスコネクトノード)のスイッチ規模を抑制するには，内包する波長パスの入れ換え(グルーミング)を行う波長群パスの割合(グルーミング率)に上限を設けることが本質的であることが知られている [梯他'08]．グルーミング率の制約は優れた波長群パス・波長パスの配置アルゴリズムを要求するが，最近の検討 [L. H. Chau 他'08] により，波長群番号に依らず定義されるグルーミング率の制約を想定する時，小さなグルーミング率であっても効率の良い波長群パス収容が実現できることが示されている．そこで本稿では，波長群番号に依らず定義されるグルーミング率の制約を実現するコンパクトな階層型光クロスコネクトノード構成と，波長群番号への依存性を解決する新たな波長合分波器デバイスを提案する．従来型 1 階層光クロスコネクトノード構成及び階層型光クロスコネクトノード構成と，提案ノード構成のスイッチ規模比較により，その優位性を示す．本稿では同時に，提案ノード構成のプロトタイプシステムを構築し，伝送実験を行い，良好な伝送特性を確認する．
キーワード 階層型光クロスコネクトノード，波長群，グルーミング率制約

Hierarchical Optical Cross-Connect Node Architecture Considering Grooming Ratio Restriction

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Abstract In order to cope with the further traffic expansion due to the introduction of future broadband services such as IP-TV/VoD, hierarchical optical path networks that utilize waveband paths, groups of multiple wavelength paths, have been investigated. It was shown that node switch scale of the hierarchical optical path network node (Hierarchical Optical Cross-Connect: HOXC) can significantly be reduced when the grooming ratio, the ratio of number of groomed waveband paths to that of all incoming/outgoing waveband paths, is restricted [S. Kakehashi et al., 2008]. A recent work [L. H. Chau et al., 2008] elucidates that network with colorless grooming ratio restriction, which defines grooming ratio regardless of the waveband index, can offer high efficiency of path utilization by utilizing a new effective design algorithm. In this paper, we develop a novel matrix-switch-based HOXC architecture and wavelength MUX/DMUX that implement the colorless grooming ratio restriction. Numerical evaluations demonstrate that our proposed HOXC can significantly reduce node switch scale compared not only to the single-layer optical path network node (single-layer OXC) but also the conventional HOXC node that offers the same restriction. We also developed a prototype system of the proposed HOXC node and performed transmission experiments to verify its good transmission characteristics.
Keyword Hierarchical Optical Cross-Connect Node, Waveband, Grooming Ratio Restriction

1. Introduction

Due to the rapid penetration of broadband access, traffic has increased explosively. In order to cope with the future traffic increase due to the introduction of future broadband services such as IP-TV/VoD, which uses ultra- high definition TV (60-72 Gbps/ch, uncompressed), hierarchical optical path networks that introduce waveband paths, multiple of wavelength paths, have been investigated [1, 2]. The hierarchical optical cross-connects (HOXCs) consist of waveband cross-connects (WBXCs) and wavelength path cross-connects (WXCs). It was shown that node switch scale can significantly be reduced when the grooming ratio at WBXC, the ratio of number of groomed waveband paths to that of incoming/outgoing total waveband paths, is restricted [3, 4] (for example, the switch scale can be reduced to about 1/2, when the grooming ratio restriction is 0.25). The grooming ratio restriction can be done in three ways; colorless grooming ratio restriction, grooming ratio restriction on each waveband or on each fiber. The first restriction covers all waveband paths coming to (outgoing from) the node while the second and third ones are on each waveband and each fiber, respectively. Wavelength/waveband selective switch (WSS/WBSS) based HOXC architecture can exploit only the third restriction while matrix switch based architecture can exploit all restrictions and hence offers much more flexible routing capability. From the network design point of view, the restriction tend to increase network cost, however, a recent work [5] shows that the colorless grooming ratio restriction can hardly increase network cost by utilizing a new effective design algorithm.

Considering the switch scale reduction possible with HOXC and to maximize the flexibility in routing, we develop a novel matrix-switch-based HOXC architecture that implements the colorless grooming ratio restriction. This is attained when each MUX/DMUX in WXC, connected to WBXC, can process any waveband (namely the colorless MUX/DMUX in terms of waveband). We newly develop a novel AWG based MUX/DMUX that can be used by any waveband. Numerical evaluations demonstrate that our proposed HOXC can reduce node switch scale significantly compared not only to the single layer OXC but also the conventional HOXC that offers the same restriction. We also verified the performance of the prototype HOXC: its power penalty (BER= 10^{-9}) was less than 0.2 dB after traversing 5 nodes including one grooming node. A detailed report on this HOXC has been published as a journal paper [6].

2. Matrix-switch-based OXC architecture

2.1 Conventional Single-Layer OXC Architecture

In this section, we review two conventional single-layer OXC architectures. Let K be the number of incoming/outgoing fibers, M the number of waveband paths per fiber, and N the number of wavelength paths per waveband. Suppose that x is given as the upper bound of the ratio of added/dropped wavelength paths to all incoming/outgoing wavelength paths (wavelength add/drop ratio) for single layer OXC. Figure 1 and 2 shows two single-layer OXCs. Considering the reduction of switch scale, we assume that the number of add/drop ports is less than that of ports for incoming/outgoing paths, namely $x < 1$.

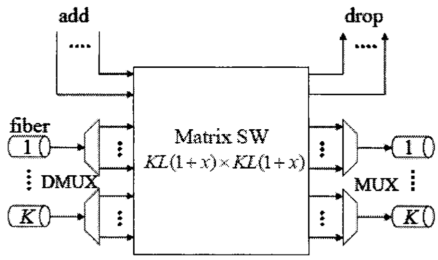


Fig. 1 Single-layer OXC with a large matrix switch (type S1)

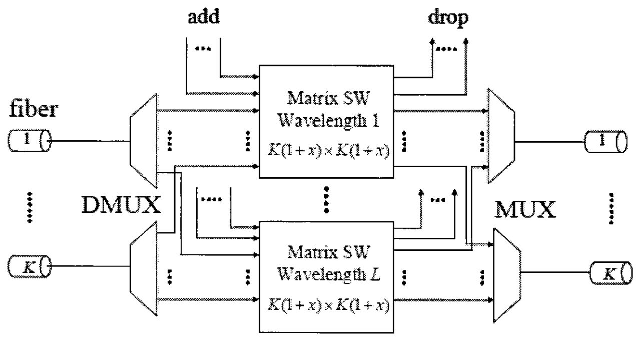


Fig. 2 Single-layer OXC that consists of matrix switches dedicated to the same-wavelength paths (type S2)

Figure 1 shows a single-layer OXC consisting of a single large matrix switch, which can connect optical paths from any input or add port to any output or drop port. Therefore, it realizes the most flexible add/drop capability that can add/drop any combinations of wavelength paths. We call this single-layer OXC type S1.

Figure 2 shows a single-layer OXC where a large matrix switch in type S1 is divided into small switches dedicated to each wavelength. We call this single-layer OXC type S2. Although type S2 can reduce switch scale compared to type S1, the number of added/dropped wavelength paths is bounded for each wavelength, and hence the add/drop restriction is much tighter than that in type S1.

2.2 Conventional HOXC architecture [4]

In this section, we briefly review a conventional HOXC architecture with colorless grooming ratio restriction. Figure 3 shows the conventional HOXC architecture. Let y and z be the upper bounds for the colorless grooming ratio and the wavelength

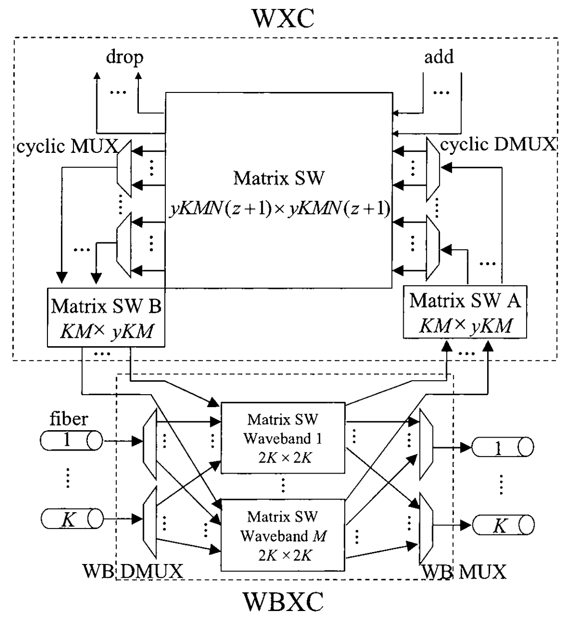


Fig. 3 Conventional HOXC architecture [4]

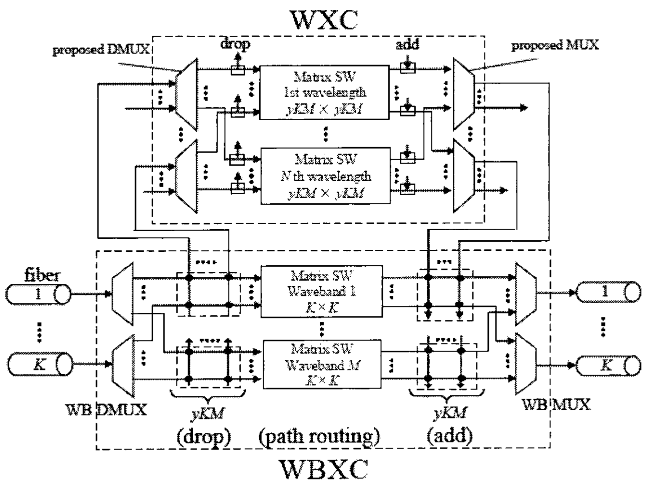


Fig. 4 Proposed HOXC architecture

add/drop ratio for WBXC and WXC of HOXC, respectively. Hereafter, we assume that $x = y$ and $z = 1$ to maximize switch scale reduction by HOXC [4]. Given sets of wavelengths, $\{\lambda_1, \lambda_2, \ldots, \lambda_{MN}\}$ can be classified into continuous wavebands $\{\lambda_{iN+1}, \lambda_{iN+2}, \ldots, \lambda_{(i+1)N}\}$ (i =0, 1, …, M-1) or interleaved wavebands $\{\lambda_{i+1}, \lambda_{i+M+1}, \ldots, \lambda_{i+M(N-1)+1}\}$ (i = 0, 1,…, M-1) [2]. The selection of waveband type has no impact on network design or operation. The HOXC architecture consists of matrix switches, each of which is dedicated to one waveband, two matrix switches, which restrict the number of added/dropped wavebands, and a WXC with a single large matrix switch. Thanks to the matrix switches, the configuration satisfies the colorless add/drop restriction.

The colorless grooming capability requires each MUX/DMUX in WXC to be able to multi-/demultiplex any waveband path with different waveband indexes. That is, regardless of waveband index, it must be possible to freely distribute wavelength paths in a waveband to the output ports of the DMUX where the number of ports equals that of wavelength paths. However, the architecture is possible only with the continuous waveband arrangement and requires cyclic AWGs in WXC part. The switch scale reduction has been analyzed [4] and a large matrix switch is necessary for realizing the colorless wavelength add/drop capability in the WXC part. The relatively large switch scale is an issue to be resolved.

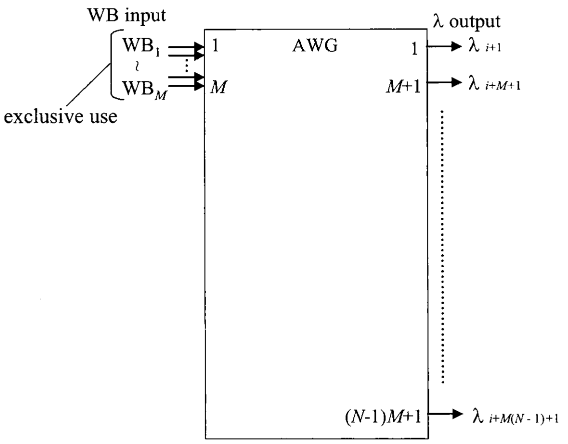
2.3 Proposed HOXC Architecture

We briefly review our compact HOXC architecture and its advantages. Figure 4 shows the proposed HOXC architecture. There are three major differences between the proposed and conventional HOXC architecture [4]; 1) WXC consists of N smaller matrix switches where the i-th switch is shared by i-th wavelength paths in any incoming wavebands (please note that grooming is done among same wavebands), 2) a colorless MUX/DMUX that can be commonly used by all wavebands to attain colorless grooming, 3) matrix switches specially designed for grooming operations, which corresponds to matrix switches between WBXC/WXC in Fig. 3 that are required for attaining colorless grooming.

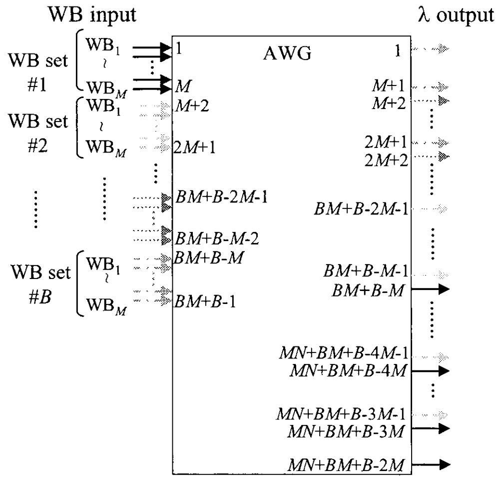
Considering item 2), output port set of the DMUX in WXC must be unique and fixed for all incoming wavebands, which allows us to utilize the common matrix switches in WXC. Figure 5 (a) shows the proposed colorless wavelength MUX/DMUX for the interleaved waveband arrangement. For the continuous waveband configuration, the MUX/DMUX can be realized in a similar way. Practical integration is discussed later.

3. Switch scale evaluation

In this section, we compare the switch scale of the four OXC architectures discussed in the previous sections. Here we utilize the number of cross-points as the measure of total switch scale. Parameter values are assumed as; K=10, M=4, N=16. Figure 6 shows analyzed switch scale plotted on a logarithmic scale for the four OXCs. It shows that the single-layer OXC and HOXC architectures, type S1 and type H1, that adopt large matrix switches require much larger scales. It should be noted that these switch architectures allow colorless/contentionless/directionless optical path add/drop capabilities [7] that are useful for dynamic optical path operations. The flexibility can be attained not only with large matrix type optical switches, but also with electrical switches including simple matrix type electrical switches [8], and SDH/SONET and ODU cross-connects [9]. The introduction of



(a) Input ports arranged as single MUX/DMUX



(b) Multiple MUXs/DMUXs

Fig. 5 Integration of multiple MUXs/DMUXs onto an AWG (for interleaved waveband arrangement)

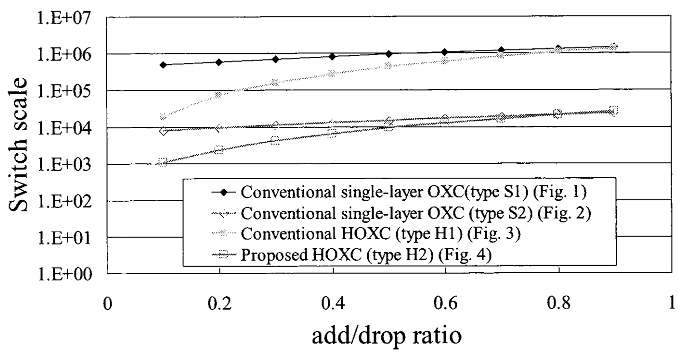


Fig. 6 Switch scale evaluation (from Figs. 1, 2, 3, and 4)

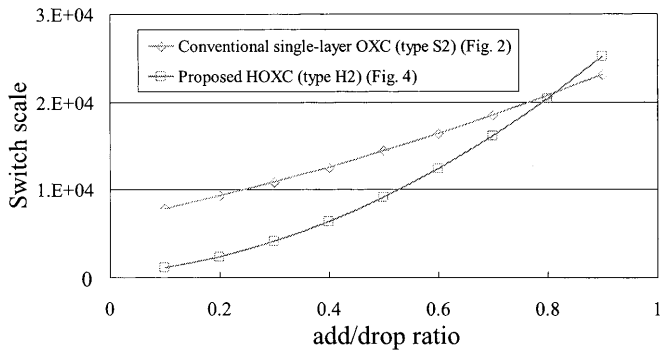


Fig. 7 Switch scale evaluation (from Figs. 2 and 4)

electrical equipment requires additional intra-office optical links, which are much less expensive than transponders used for inter-office transmission, between electrical switches and client node systems such as routers. The electrical cross-connect may be required from the service point of view to attain sub-lambda granularities [10]. Figure 7 plots switch scale on a linear scale for the two other architectures, type S2 and type H2. For these architectures, additional mechanisms are necessary to attain colorless/contentionless/directionless optical path add/drop capabilities, but various solutions including electrical technologies exist [8, 10] as mentioned above. We, therefore, focus on the switch functions that are necessary to cross-connect optical paths that traverse the node. In Fig. 7, when $x=y=0.2$, the proposed HOXC architecture has 75% smaller switch scale than the single-layer OXC's. Please note that the single-layer OXC architecture, type S2, imposes a tighter restriction that is defined for each wavelength, while the proposed HOXC only imposes a colorless grooming ratio restriction, which allows any combination of waveband paths to be added/dropped.

Recent studies considering grooming ratio values revealed that in a network that utilizes waveband routing, the grooming ratio can be restricted to a small value, say 0.2, that it virtually does not decrease the efficiency of path utilization by utilizing an appropriate network design algorithm considering the grooming ratio restriction [5]. In other words, the use of small-scale wavelength-grooming switches (WXCs) in HOXC was shown to offer a new approach to the creation of optical networks that accommodate a large number of optical paths [11]. Particularly in this regard, the proposed HOXC (type H2) is proven to be very effective.

4. Integration of colorless wavelength MUX/DMUX

In this paper, we propose a simple method to integrate multiple colorless wavelength MUXs/DMUXs on one AWG chip. We start with the observation that with fixed spacing between two input port sets, we can guarantee that their output port sets do not overlap. Figure 5 (b) shows the proposed integrated device that attains the dense utilization of output ports. When M=5, N=8, the port utilization for a single AWG colorless wavelength MUX/DMUX is 13%, while that increases to 35% when four MUXs/DMUXs are integrating onto a AWG. The integrated arrangement reduces footprint and cost. This scheme can be easily extended to cover the continuous waveband configuration.

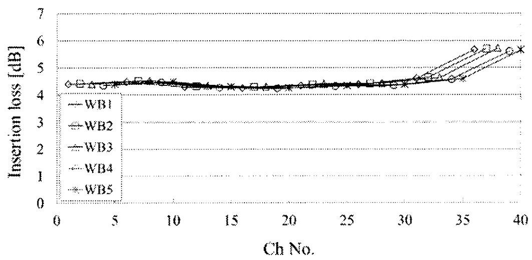


Fig. 8 Insertion loss of colorless MUX/DMUX

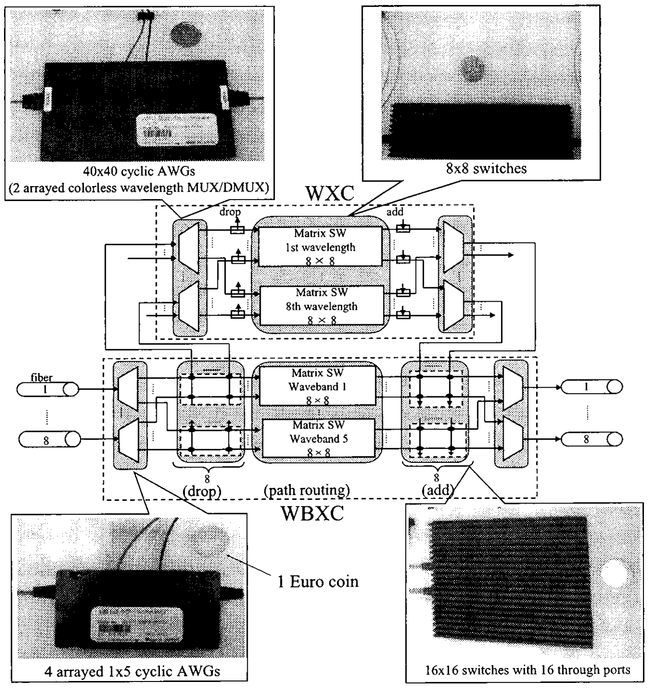


Fig. 9 Developed prototype HOXC architecture

5. Realization of prototype HOXC system and transmission experiment

1) Integrated colorless wavelength MUX/DMUX

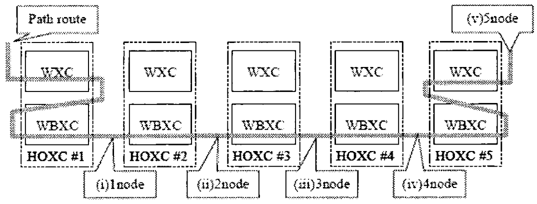
We developed AWG colorless wavelength MUXs/DMUXs on a 40 x 40 AWG, each of which integrates one MUX and one DMUX. Fourty 100-GHz spaced channels (191.7+0.1 x n THz; n = 0~39) on an ITU-T grid are used. The 40 wavelengths are divided into five WBs, each of which consists of 8 channels. Figure 8 shows the insertion loss of one of the colorless MUX/DMUX. The insertion loss increases by about 1 dB for 8th-wavelength path of each waveband, but the maximum loss was less than 6 dB.

2) Matrix switch with through ports

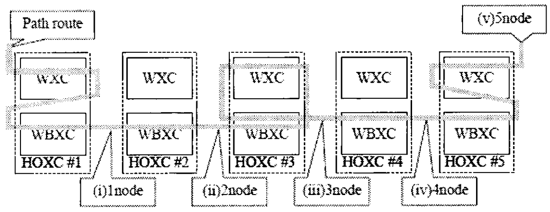
We develop a novel matrix switch having through ports for the grooming operation, see in Fig. 9. By utilizing this switch in the proposed HOXC architecture, the grooming function in WBXC can be realized with smaller switches than is possible with the conventional HOXC architecture.

3) Prototype HOXC

Figure 9 shows the proposed HOXC prototype that accommodates 8-input and 8-output fibers (degree 8). It consists of thirteen 8 x 8 matrix switches, ten 16 x 16 matrix switches with 16 through ports, four 4-arrayed 1 x 5 waveband MUXs/DMUXs, and eight integrated 40 x 40 AWGs (each accommodates colorless wavelength two MUXs/DMUXs).



(a) End-to-End connection



(b) With one time intermediate grooming

Fig. 10 Transmission testbed

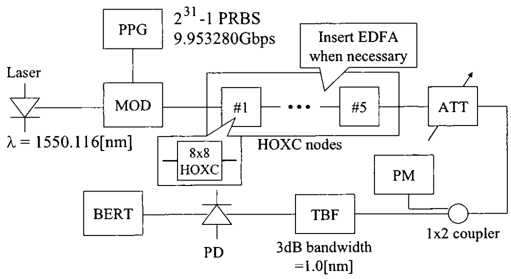
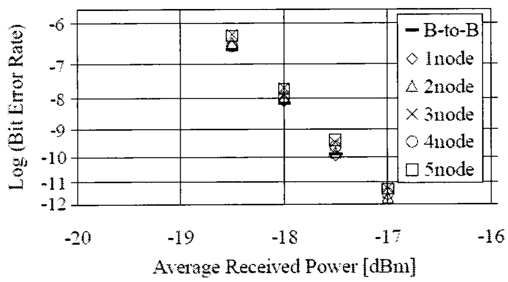
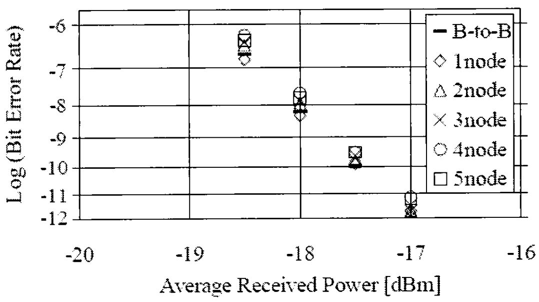


Fig. 11 Experimental setup for BER evaluation

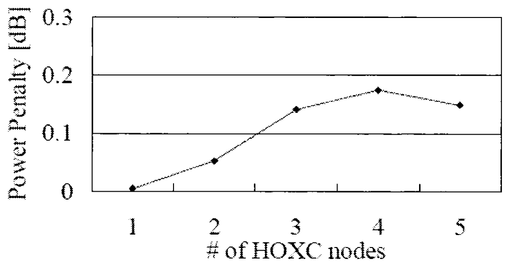


(a) End-to-End connection

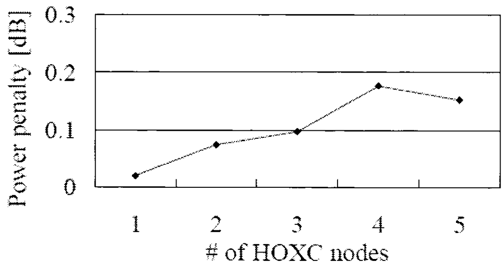


(b) With one time intermediate grooming

Fig. 12 BER measurements



(a) End-to-End connection



(b) With one time intermediate grooming

Fig. 13 Power penalty

4) Transmission experiment

We assessed the transmission characteristics of two typical path configurations, see Figure 10: (a) optical path connected between source and destination node pairs using direct end-to-end waveband, and (b) optical path with intermediate grooming. BER and power penalty were measured at each measurement point from (i) to (v) in Fig. 10. The experimental setup used is shown in Fig. 11 where the five boxes, #1 to #5, stand for the HOXC nodes in Fig. 10. Figures 12 (a) and (b) show the evaluated BER and Figures 13 (a) and (b) plot the power penalty at the BER of 10^{-9} versus the number of HOXC hops. With and without intermediate grooming, power penalties are less than 0.2 dB after traversing 5 nodes.

6. Conclusions

We propose a novel compact HOXC architecture and demonstrate a prototype system with integrated multiple colorless wavelength MUXs/DMUXs. Transmission experiments confirmed the technical feasibility and good transmission characteristics of the proposed HOXC system. This HOXC will be suitable for creating cost-effective backbone networks.

Acknowledgment

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