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CALCULATION METHOD FOR WAVELENGTH PATH WITH TRANSIT NODES AND ITS ACCUMULATED OPTICAL LOSS IN AWG-STAR NETWORK WITH LOOPBACK FUNCTION

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Abstract. *Lately, in order to tackle the surge in information and communication traffic, various researches and developments have been conducted to expand the communication channel capacity and ensure its effective distribution in communication network. We proposed the AWG-STAR network with loopback function to meet such capacity requirements for relatively small-scale networks. The proposed network can relocate wavelength paths in response to traffic demand by remotely controlling inexpensive optical switches to avoid traffic congestion and inefficient consumption of communication capacity that lead to degradation of communication service quality. However, network management and maintenance of the AWG-STAR network would be substantive due to its complex wavelength path topology and the accumulated optical loss of wavelength path changes due to wavelength path relocation. In this study, we propose a method for calculating the wavelength path with transit nodes and the accumulated optical loss along the wavelength paths in the AWG-STAR network with loopback function in order to reduce workload and make the wavelength path easier to manage. We also developed an application software based on the calculation method, and evaluated its calculation time performance. Furthermore, we constructed an AWG-STAR network for conducting experiments and verified adequacy of the calculation method by comparing calculated results with measured values of accumulation optical loss along the wavelength path.*
Keywords: Arrayed waveguide grating, Wavelength division multiplexing, Wavelength transfer matrix, Ethernet, IP

1. **Introduction.** The amount of information and communication traffic around the world has been remarkably increasing. In Japan, the gross downloading traffic among broadband subscribers was 9.60 Tbps (May 2017), according to the statistics provided by the Ministry of Internal Affairs and Communications in Japan regarding network traffic [1]. This is 1.40 times larger than the traffic in May 2016 (6.88 Tbps) and 15.21 times larger than that reported in May 2007 (0.63 Tbps). A similar trend shows gross upload traffic of 1.80 Tbps in May 2017, which is 1.36 times larger than the one in May 2016 (1.32 Tbps) and 4.00 times larger than that of May 2007 (0.45 Tbps).

Considering the increasing traffic, information and communication network is necessary to expand the communication channel capacity and suitably distribute the capacity to pairs of communication nodes according to traffic demand. Optical communication techniques such as optical fiber, optical transceiver, and various multiplexing devices such as

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wavelength division multiplexing (WDM) and space DM (SDM) are being used to expand the channel capacity of networks [2,3]. Today, WDM technologies have become common in large traffic distribution networks. Besides, to achieve effective distribution of communication channel capacity, reconfigurable optical add/drop multiplexer (ROADM) has been proposed for flexible relocation of wavelength paths based on the traffic demand [4]. However, ROADM generally targets relatively large-scale networks (e.g., core networks and metropolitan area networks) than relatively small-scale networks (e.g., local area, enterprise, and university campus networks). ROADM is also generally very expensive, because ROADM includes many expensive optical components and high functionality software. Therefore, total cost for network construction including the ROADMs becomes phenomenally expensive. If the ROADM is used in the small-scale network in which the number of users is far less than that of the large-scale network, the cost per user in the small-scale network becomes high. Therefore, a cost-effective solution is required for small-scale networks. We have been studying IP/Ethernet over coarse WDM network [5,6,19] with a cost-effective ROADM [7,8] employing inexpensive optical switches. In recent years, we have proposed an arrayed waveguide grating (AWG)-STAR network with loopback function employing inexpensive optical switches and a cyclic-frequency AWG to provide the flexible wavelength path relocation function and the channel capacity expansion for small-scale networks [9]. Performance evaluation of the wavelength path relocation was conducted with an experimental network that we constructed in our laboratory based on the proposed AWG-STAR [10]. Semiconductor optical amplifier was introduced in the AWG-STAR network for high scalability [11]. Remote control systems for simple management in the AWG-STAR network were also developed [12-14].

Generally, the AWG-STAR network has many wavelength paths with a very complicated topology that is made more complicated by frequent wavelength path relocations, leading to accumulated optical loss with each change along the wavelength path. As a result, management and maintenance of the network involve a very heavy workload, and conventional management methods that employ management information base (MIB) for IP/Ethernet network cannot be used as the MIB that is equipped in routers for small-scale networks generally does not support optical layer information about the wavelength paths. A wavelength path management system is required to reduce workload for the network administrators. Detection of wavelength path topology is an important function of management systems. For carrying out the detection function, a calculation method for wavelength path topology using wavelength transfer matrix was proposed for an AWG-STAR network with fixed wavelength path topology [15]. However, the calculation method in [15] could not be directly applied to the AWG-STAR network we proposed, because it could not express a relocation of a specific wavelength path. So, we proposed a calculation method suitable for AWG-STAR network with dynamic changeable wavelength path topology by wavelength path relocation function [16], based on [15]. Although there were other reports [17,18] based on [15], both of them provided the contributions for an AWG-STAR network with fixed wavelength path topology. Our proposed method [16] enables network administrator to calculate and manage easily the dynamic changeable wavelength path topology. Although that method [16] was able to obtain the wavelength path topology, it was not able to calculate the transit nodes and accumulated optical loss along each wavelength path. It is very important to manage the optical loss accurately. The optical loss attenuates the power of optical signal. When the optical power received at optical transceiver in the wavelength path is lower than a minimum light reception power of the optical transceiver, the wavelength path is disable. The accumulated optical loss depends on the transit nodes and the length of the optical fiber in each wavelength path. Furthermore, the accumulated optical loss determines the flexibility of the wavelength path relocation [11]. Therefore, the network administrator must manage the optical loss corresponding to transit nodes and the optical fiber included in the wavelength path in order to maintain the capability for data communication. In this study, we propose an enhanced calculation method based on [16], which can obtain wavelength path with transit nodes and its accumulated optical loss along each wavelength path easily such that the network administrator can reduce network management workload, maintenance, and troubleshooting of AWG-STAR network with wavelength path relocation function.

In Section 2, we provide an outline of the AWG-STAR network with loopback function. In Section 3, we propose the improved calculation method and report the performance of an application software based on the calculation method. In Section 4, we describe an experimental network based on the AWG-STAR network, and confirm the adequacy of the calculation method by comparing the values obtained in the experimental network with the calculated values of the software and finding both values in near agreement. In Section 5, we summarize our conclusions and provide avenues for future work.

2. **AWG-STAR Network with Wavelength Path Relocation Function.** AWG is an optical device used in optical fiber network with WDM technology. Generally, AWG has n input/output ports (InP/OutP) and n wavelengths multiplexing/demultiplexing function in each port. InP-x and OutP-x are both connected to node-x employing two optical fibers. In addition, AWG has a wavelength routing function. N wavelengths input to an InP of the AWG are demultiplexed inside AWG, and then each wavelength is output from a different respective OutP. For example, as shown in Figure 1(a), when n wavelengths ($\lambda_1, \ldots, \lambda_n$) are input to InP-1, λ_1 is output to OutP-1, λ_2 is output to

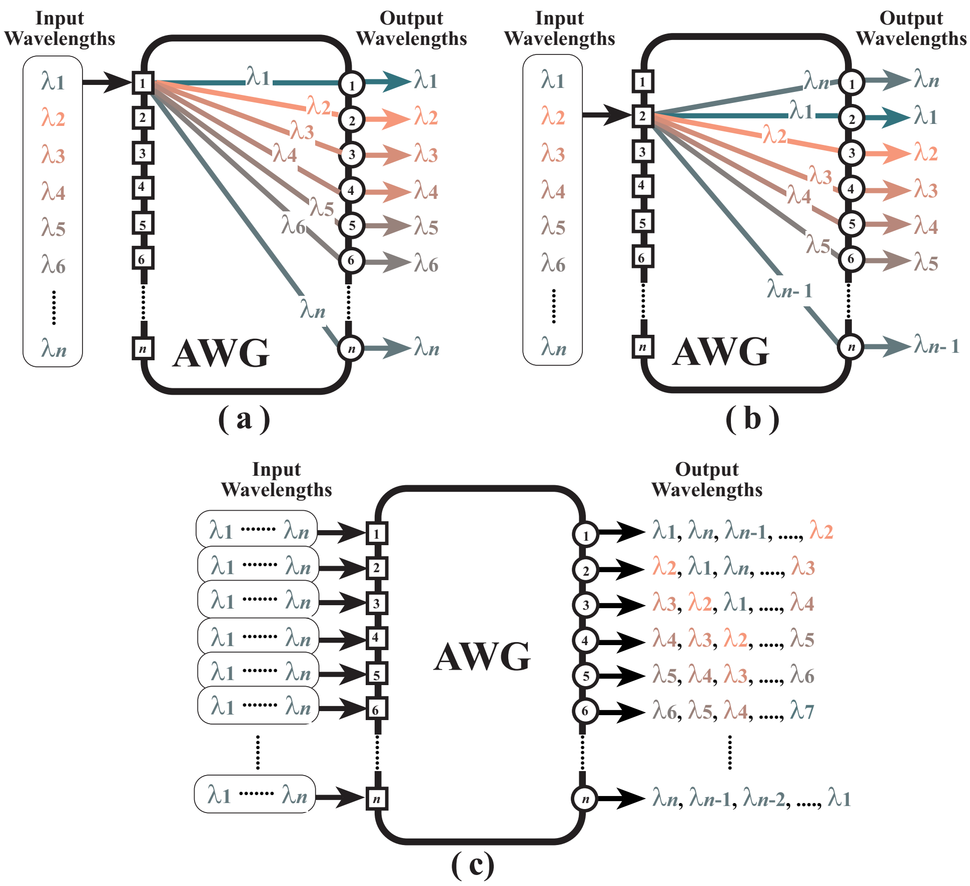

FIGURE 1. Wavelength routing function of AWG

OutP-2, and λ_n is output to OutP-n. As a result, wavelength paths connecting node 1 and other nodes of different wavelengths are observed. Generally, as shown in Figure 1(b), wavelength routing function of AWG has a wavelength cyclical characteristic. N wavelengths input to InP-2 are output to different respective OutP, and the OutP is next OutP to which the same wavelength from InP-1 is output. As a result, as shown in Figure 1(c), if n wavelengths are input to all n InPs, then all the nodes are interconnected by the wavelength paths, and the wavelength path topology becomes a full mesh.

Figure 2 shows the topologies of the AWG-STAR network which are covered in this study. As shown in Figure 2(left), each node is physically connected to the AWG by a pair of optical fibers with STAR topology. Based on the physical topology, a full mesh wavelength path topology (Figure 2(center)) is formed by the wavelength routing function of the AWG described above. We have proposed an AWG-STAR network with loopback function that can adjust communication channel capacity between specific nodes according to traffic demands by wavelength path relocation. For example, as shown in Figure 2(right), wavelength paths from nodes 1 to 6, 6 to 3, 3 to 8, and 8 to 5 are integrated to form one wavelength path that is relocated between nodes 1 and 5. Wavelength path relocation can expand two times the communication channel capacity between nodes 1 and 5.

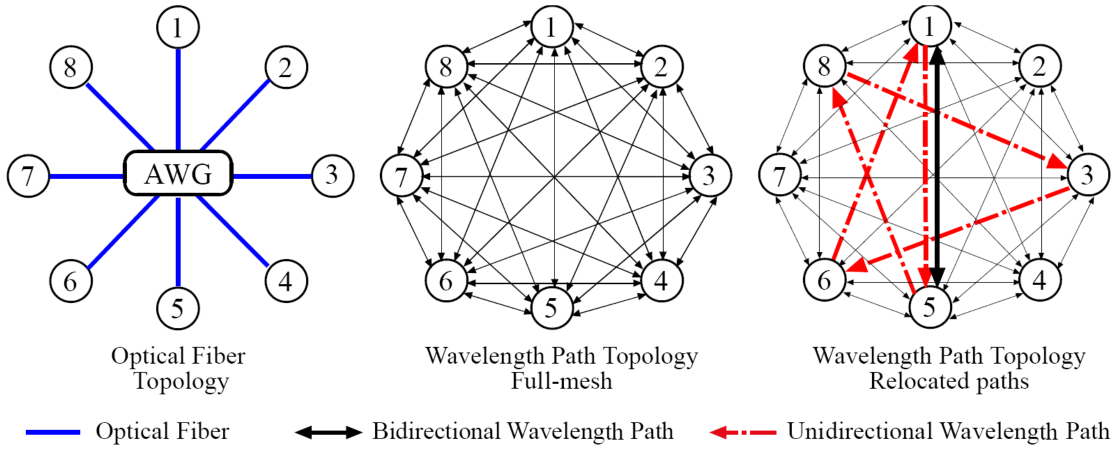

FIGURE 2. Topology of the AWG-STAR network with loopback function

Figure 3 shows the node configuration of our proposed AWG-STAR network. AWG-STAR network targets relatively small-scale networks, such as university campus and business networks. A node is allotted to each building, and it comprises internal local networks and a gateway. The local networks exchange traffic with other nodes via the gateway. The gateway consists of an optical add/drop multiplexer (OADM), optical switches (OSW), and a layer-3 switch (L3SW). The L3SW in each node transfers traffic between the local networks and other nodes. Optical transceivers (OTR) equipped in the L3SW convert electric signals to optical signals and the OADM multiplexes and demultiplexes multiple wavelengths. N wavelengths transferred from the AWG to OADM are demultiplexed and are input to a correspondent OSW for each wavelength, whereas N wavelengths input from OSW are multiplexed in OADM and are transferred to AWG. Since one OSW corresponds to one wavelength, there are n OSWs in each node. Therefore, the number of OSWs in the network is $n \times n$ when the number of nodes is n. Each OSW has two states depending on port connection. When the connection state is C_{PT} (Figure 3), the wavelength from OADM passes through the OSW and is input to OTR equipped in L3SW. When the connection state is C_{LB}, the wavelength from OADM is looped back

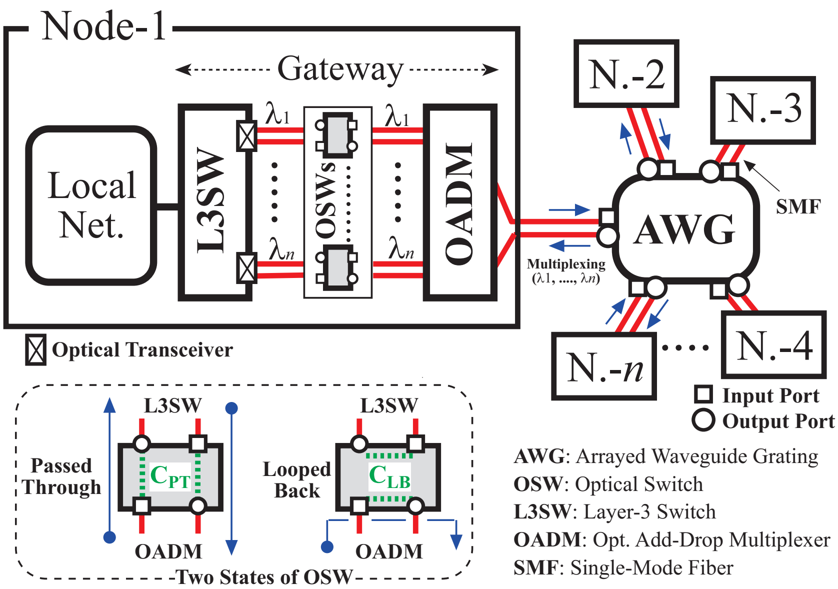

FIGURE 3. Node configuration of the AWG-STAR network

inside OSW and is input to AWG again via OADM. For example, the wavelength λ_2 which is input into InP-1 from node 1 as shown in Figure 1(a) is routed to node 2 by the routing function of AWG, then λ_2 is received in node 2 when the state of OSW corresponding to λ_2 in node 2 is C_{PT}. On the other hand, λ_2 is looped back to the AWG when the state of the OSW is C_{LB}, and then, λ_2 is input into InP-2 as shown in Figure 1(b). As a result, λ_2 is also routed and is received in node 3. When the states of OSWs corresponding to λ_2 and λ_3 are C_{PT} in node 3, the number of wavelength paths between nodes 1 to 3 is two. As a consequence, the communication channel between nodes 1 to 3 is expanded by the wavelength path relocation. The mechanism of the wavelength path relocation is described in more detail in [13,16].

3. Calculation Method for Wavelength Path with Transit Nodes and Its Accumulated Optical Loss. Wavelength path topology can be calculated by employing the matrix representation for AWG-STAR network with loopback function as described in [16]. However, the matrix representation method cannot calculate transit nodes and accumulated optical loss along each wavelength path. It is very important to manage the optical loss accurately because each wavelength path cannot be enabled until the optical power received at OTR in L3SW is more than the minimum light reception power of the OTR.

By obtaining detailed information about wavelength path with transit nodes and accumulated optical loss, it is possible to efficiently determine the cause of network failure and to identify the network device that needs renovation. For example, when a wavelength path is invalid but the electrical devices related to the wavelength path such as L3SW are normal, it indicates issues with the optical devices. One troubleshooting strategy is to compare the known minimum light reception power of OTR with the actual measured light reception power at OTR, calculate their difference, and then find the optical device that has an optical loss value equivalent to the differential light power along the wavelength path. Similarly, when the actual measured light reception power at OTR is zero and the wavelength path is invalid (often due to a transit node or optical fibers), the cause of failure can be located by tracing the invalid wavelength path from the OTR. For this reason, it is very important that transit nodes and accumulated optical loss along each wavelength path are managed at a granular level without overburdening management and maintenance of the AWG-STAR network. We therefore propose a calculation method for wavelength path with transit nodes and the accumulated optical loss of the wavelength path based on the matrix expression of [16] to manage wavelength path information.

In this study, it is assumed that the number of nodes is N and the number of wavelengths is Λ in the AWG-STAR network with loopback function. First, we propose the AWG's wavelength routing characteristic matrix expressed as Equation (1).

$$\boldsymbol{L} = \begin{pmatrix} OP_{1-1} & OP_{1-2} & OP_{1-3} & \cdots & OP_{1-\Lambda} \\ OP_{2-1} & OP_{2-2} & OP_{2-3} & \cdots & OP_{2-\Lambda} \\ OP_{3-1} & OP_{3-2} & OP_{3-3} & \cdots & OP_{3-\Lambda} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ OP_{N-1} & OP_{N-2} & OP_{N-3} & \cdots & OP_{N-\Lambda} \end{pmatrix} \tag{1}$$

$\boldsymbol{L}$ is an $N \times \Lambda$ matrix. The row of $\boldsymbol{L}$ indicates transmitting nodes, and the column of $\boldsymbol{L}$ indicates wavelengths. The element OP_{i-j} indicates that wavelength j input from node i to AWG is output from OutP-OP_{i-j} in AWG to node OP_{i-j} as a result of being routed.

The terminal connection state matrix of OSW is expressed as Equation (2).

$$\boldsymbol{S} = \begin{pmatrix} s_{1-1} & s_{1-2} & s_{1-3} & \cdots & s_{1-\Lambda} \\ s_{2-1} & s_{2-2} & s_{2-3} & \cdots & s_{2-\Lambda} \\ s_{3-1} & s_{3-2} & s_{3-3} & \cdots & s_{3-\Lambda} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ s_{N-1} & s_{N-2} & s_{N-3} & \cdots & s_{N-\Lambda} \end{pmatrix} \tag{2}$$

$\boldsymbol{S}$ is also an $N \times \Lambda$ matrix. The row of $\boldsymbol{S}$ indicates transmitting nodes, and the column of $\boldsymbol{S}$ indicates wavelengths. The element s_{i-j} indicates the terminal connection state of OSW, which is $\mathrm{C_{PT}}$ or $\mathrm{C_{LB}}$. When the terminal connection state of OSW is $\mathrm{C_{PT}}$, s_{i-j} is 0; when it is $\mathrm{C_{LB}}$, s_{i-j} is 1. For example, when the wavelength path topology in the AWG-STAR network is full-meshed, all the elements of $\boldsymbol{S}$ are 0 because the terminal connection states of all OSWs are $\mathrm{C_{PT}}$.

Next, we propose a calculation method for wavelength path with transit nodes and its accumulated optical loss. Figure 4 shows the calculation flow. To begin with, the calculation parameters are initialized. N is the number of nodes, and Λ is the number of wavelengths. $\boldsymbol{L}$ is determined by the wavelength routing characteristic of AWG used in a target network. And, $\boldsymbol{S}$ is also determined by initial wavelength topology of the target network. The optical loss database is constructed by values of optical devices used in the target network. At final initialization, both of loop counters as i and j are set to 1. The parameters of i and j indicate source node number and wavelength number, respectively. After parameter initialization, the flow advances to next stage as finding wavelength path with transit nodes. Variable number r is set to i. Element OP_{r-j} corresponding to node r and wavelength j in $\boldsymbol{L}$ gives the output node to which wavelength j is transmitted from OutP-OP_{r-j} in AWG, and the output node is added to wavelength path with wavelength j and source node i as a transit node. The node number of the output node is assumed to $r(next)$ here. And then, element $s_{r(next)-j}$ corresponding to the output node $r(next)$ and wavelength j in $\boldsymbol{S}$ is checked. If element $s_{r(next)-j}$ is equal to 0, it indicates that wavelength j is received at the last node which is the destination, and it also indicates that the wavelength path with wavelength j from source node i has been determined. If element $s_{r(next)-j}$ is equal to 1, element $OP_{r(next)-j}$ corresponding to wavelength j in row $r(next)$ of $\boldsymbol{L}$ is found, because wavelength j is looped back in node $r(next)$, and it is input to InP-$r(next)$ in the AWG. By executing these steps for all wavelengths and source nodes, all wavelength paths with transit nodes can be found. Next, the flow advances to next stage as calculating accumulated optical loss, after loop counters of i and j are initialized again. All of optical devices are found in wavelength path corresponding to source node i and wavelength j. The optical loss value of each optical device in the wavelength path is retrieved from the optical loss database, and it is sequentially added as the accumulated optical loss until reaching the destination node. By executing the optical loss summation for all wavelength paths and source nodes, it is possible to calculate all of the accumulated optical loss in the wavelength path.

We developed an application software based on the calculation flow shown in Figure 4. Table 1 shows the application development environment. The performance related to calculation time of the application software was evaluated under the condition of the

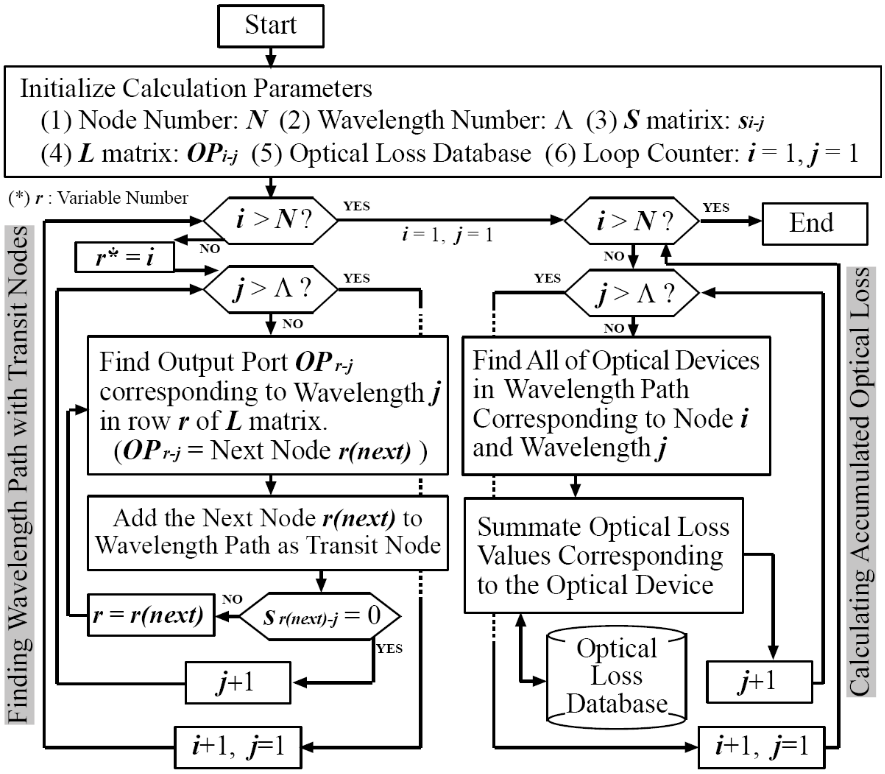

Figure 4. Calculation flow

Table 1. Development environment for the application software

Hardware	Middle-level Note-PC
Operating System	Windows 7
Programming Language	Visual Basic for Applications employing VBScript

Table 2. Optical loss database

Item	Unit	Average of Optical Loss
AWG	dB	4.5
OADM	dB	1.5
Optical Switch	dB	0.6
Optical Fiber	dB/km	0.3

Table 3. Ranges of calculation parameters

Calculation Parameters	Setting Value	Assumption
Node Number : $\boldsymbol{N}$	1 ~ 100	$\boldsymbol{N} = \boldsymbol{\Lambda}$ in this calculation
Wavelength Number : $\boldsymbol{\Lambda}$	1 ~ 100	
Size of matrix $\boldsymbol{S}$	1 x 1 ~ 100 x 100	When $\boldsymbol{N} = \boldsymbol{\Lambda} = \boldsymbol{a}$, size of these matrices is equal to $\boldsymbol{a}$ x $\boldsymbol{a}$
Size of matrix $\boldsymbol{L}$	1 x 1 ~ 100 x 100	

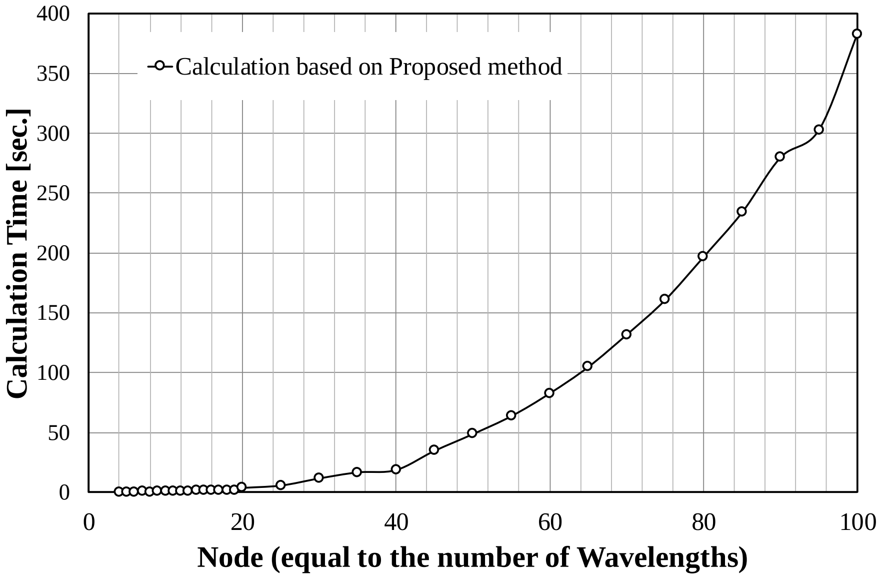

Figure 5. Calculation time of the application software

following calculation parameters shown in Tables 2 and 3. Table 2 shows the optical loss database in which the values of average optical loss correspond to the optical devices used in our AWG-STAR network. Table 3 shows the setting values of the calculation parameters. In this calculation, the number of nodes N is assumed to be equal to the number of wavelengths Λ. Figure 5 shows the measured calculation time of the application software for finding all of wavelength paths with transit nodes and all of the accumulated optical loss. Even in the case of a large-scale AWG-STAR network such as $N = 100$ and $\Lambda = 100$, the calculation was completed within a relatively short time of 383 seconds.

4. **Experiment to Evaluate the Adequacy of the Calculation Method.** The adequacy of the calculation method for wavelength path with transit nodes was evaluated by comparing with manual calculation results without application software for the calculation employing the same calculation parameters. On the other hand, the adequacy evaluation about accumulated optical losses was conducted by comparing the measured results obtained in an experimental network which was constructed based on the AWG-STAR network with loopback function and the same calculation parameters in our laboratory.

The calculation parameters were set as follows: the number of nodes ($N = 8$), the number of wavelengths ($\Lambda = 8$), and the optical losses as shown in Table 2. Table 4 shows the wavelength routing table of AWG used in the experimental network. The row of Table 4 indicates InPs of the AWG, the column indicates OutPs of the AWG, and each cell indicates the wavelength to be routed by the AWG. Wavelengths used in the network are the standard wavelength of coarse WDM [19]. For the setting about OSWs,

TABLE 4. Wavelength routing table for the experimental AWG

AWG Port	Out P1	Out P2	Out P3	Out P4	Out P5	Out P6	Out P7	Out P8
InP 1	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8
InP 2	λ_8	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
InP 3	λ_7	λ_8	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6
InP 4	λ_6	λ_7	λ_8	λ_1	λ_2	λ_3	λ_4	λ_5
InP 5	λ_5	λ_6	λ_7	λ_8	λ_1	λ_2	λ_3	λ_4
InP 6	λ_4	λ_5	λ_6	λ_7	λ_8	λ_1	λ_2	λ_3
InP 7	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	λ_1	λ_2
InP 8	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	λ_1

Label	Wavelength [nm]
λ_1	1610
λ_2	1470
λ_3	1490
λ_4	1510
λ_5	1530
λ_6	1550
λ_7	1570
λ_8	1590

OSWs corresponding to λ_2 in node 2, OSW λ_7 in node 5, and λ_7 of node 7 are set as C_{LB}, whereas the other OSWs are set as C_{PT}. Therefore, matrices $\boldsymbol{L}$ and $\boldsymbol{S}$ can be expressed as follows:

$$L = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ 2 & 3 & 4 & 5 & 6 & 7 & 8 & 1 \\ 3 & 4 & 5 & 6 & 7 & 8 & 1 & 2 \\ 4 & 5 & 6 & 7 & 8 & 1 & 2 & 3 \\ 5 & 6 & 7 & 8 & 1 & 2 & 3 & 4 \\ 6 & 7 & 8 & 1 & 2 & 3 & 4 & 5 \\ 7 & 8 & 1 & 2 & 3 & 4 & 5 & 6 \\ 8 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{pmatrix} \quad S = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

All wavelength paths with transit nodes were calculated using the above calculation parameters by our application software. Table 5 shows the calculation results of all wavelength paths. The results showed that λ_2 passed through node 2 and reached the destination node 3. It was observed that the wavelength path included node 2 as a transit node because λ_2, which was transmitted from node 1, was routed to node 2 by the AWG (shown in Table 4). It was looped back by OSW in node 2, input to InP-2 in the AWG, routed to OutP-3, and finally transmitted to node 3. The calculation results also showed that λ_7, which was transmitted from node 1, looped back by OSW in nodes 7 and 5, and eventually reached node 3. The other wavelength paths did not include any transit

TABLE 5. Calculation result about wavelength paths

Wavelength	Wavelength Path with Transit Nodes
λ_1 (1610 nm)	1 -> 1, 2 -> 2, …, 8 -> 8
λ_2 (1470 nm)	**Node *1* -> Node *2* -> Node *3***, 2 -> 2, 3 -> 4, …, 8 -> 1
λ_3 (1490 nm)	1 -> 3, 2 -> 4, …, 8 -> 2
λ_4 (1510 nm)	1 -> 4, 2 -> 5, …, 8 -> 3
λ_5 (1530 nm)	1 -> 5, 2 -> 6, …, 8 -> 4
λ_6 (1550 nm)	1 -> 6, 2 -> 7, …, 8 -> 5
λ_7 (1570 nm)	**Node *1* -> Node *7* -> Node *5* -> Node *3***, 2 -> 8, …, 4 -> 2, 5 -> 5, 6 -> 4, 7 -> 7, 8 -> 6
λ_8 (1590 nm)	1 -> 8, 2 -> 1, …, 8 -> 7

nodes. The adequacy of calculation results using application software was confirmed by comparing them with the manual calculation (without the application) employing the same calculation parameters.

We constructed an AWG-STAR network with loopback function based on the same calculation parameters mentioned above (Figure 6). Due to equipment constraint issues, only the nodes related to wavelength path relocation were constructed for this experiment. OTRs in node 1 transmitted wavelengths λ_2, λ_3, and λ_7, and OTRs in node 3 received the three wavelengths. We used 1 km, 3 km, 10 km, and 15 km optical fibers to connect each node to the AWG.

We measured the optical powers of wavelengths λ_2, λ_3, and λ_7 at various places in the experimental network. The measured results of optical power were compared with the calculated results using the accumulated optical loss as shown in Figures 7, 8, and

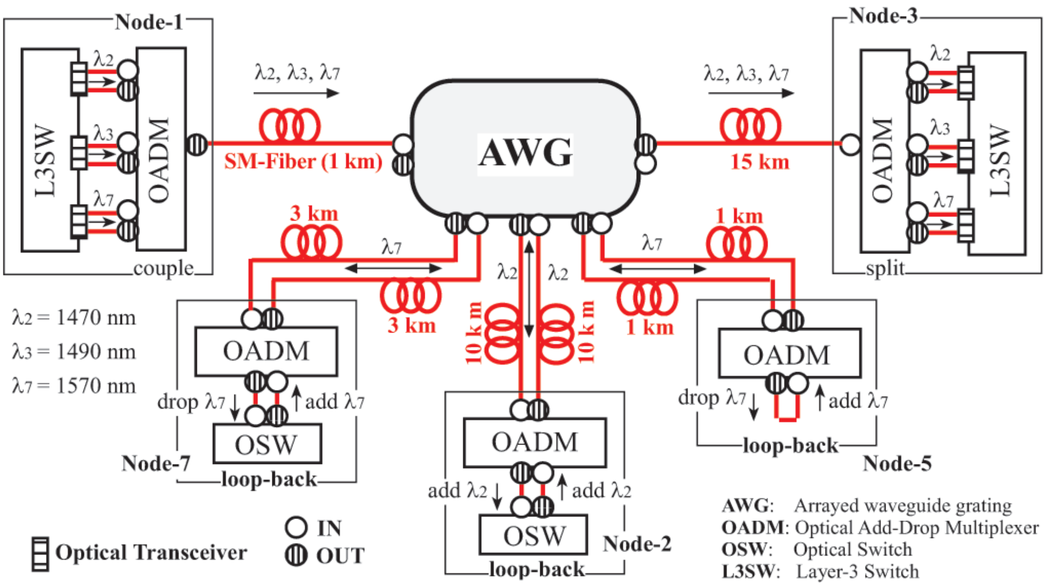

FIGURE 6. Experimental network

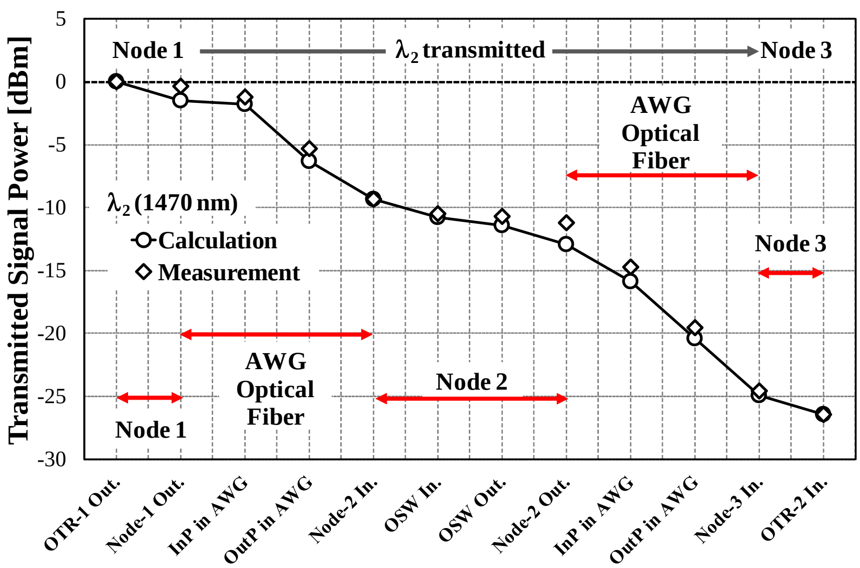

FIGURE 7. Comparison calculation with measurement about optical power along wavelength path λ_2 (1470 nm)

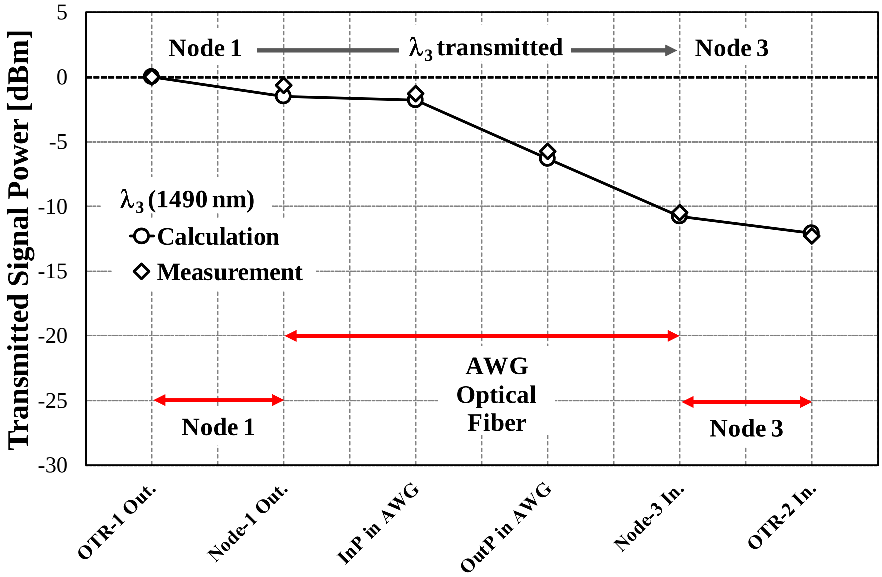

FIGURE 8. Comparison calculation with measurement about optical power along wavelength path λ_3 (1490 nm)

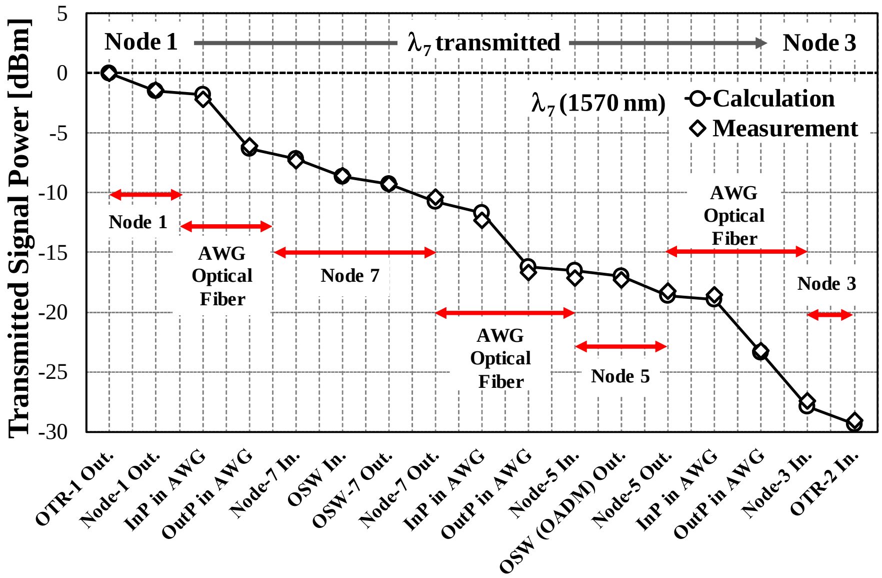

FIGURE 9. Comparison calculation with measurement about optical power along wavelength path λ_7 (1570 nm)

9. Figure 7 shows the optical powers of wavelength λ_2 between nodes 1 and 3. Figures 8 and 9 show a comparison of the results of wavelengths λ_3 and λ_7, respectively. In all of the wavelength paths, measurement and calculation results were in near agreement. Slight differences at each point may be due to the usage of the average optical loss of the optical device in the calculation instead of the micro-level where optical loss at the interconnection point of each optical device was not considered in the calculation.

The experimental results confirmed the adequacy of the proposed method for calculating wavelength path with transit nodes and its accumulated optical loss.

5. **Conclusions.** In order to reduce network management workload, maintenance, and troubleshooting of AWG-STAR network with loopback function, we proposed a method

that can calculate the wavelength path with transit nodes and its accumulated optical loss based on a matrix representation for which we developed an application software based on the proposed calculation method. As a result of evaluating the calculation time, even when considering a large-scale network with 100 nodes and 100 wavelengths, the calculation time was 383 seconds, and the calculation was completed within a practical time. To verify the adequacy of the calculation method, experiments using the AWG-STAR network with loopback function for five nodes and three wavelengths were constructed in our laboratory. We compared the calculation results of the software against no software for wavelength path with transit nodes and for accumulated optical loss in the experimental network. As a result, both of results almost agreed, confirming the adequacy of the proposed method.

In future work, we will develop the functions of automatic fault detection and automatic wavelength path relocation with information derived from the application software for wavelength path and optical loss in order to improve the remote control system [12-14] with higher functionality.

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