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MATRIX REPRESENTATION FOR WAVELENGTH PATH RELOCATION IN AWG-STAR NETWORK WITH LOOPBACK FUNCTION

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Abstract. *Research related to increasing network capacity and developing a network control function in Local Area Networks (LAN) has employed Wavelength Division Multiplexing (WDM) to handle the rapid increase in network traffic. An Arrayed Waveguide Grating (AWG)-STAR network with looping back has a function that can dynamically and flexibly rearrange a full-mesh wavelength path topology initially formed by using WDM. The function can realize a suitable topology for dealing with fluctuating traffic demands by relocating the wavelength paths. However, wavelength path relocation complicates the topology and makes it extremely difficult to manage network capacity and path relations among communication nodes. To reduce the load on network performance management, we propose a new notation with a matrix that can express the changes in path topology and in network capacity caused by wavelength path relocation. Furthermore, we describe concrete examples that apply the proposed matrix representation to an experimental network using an actual* 8×8 *AWG in order to confirm justification for the matrix representation.*
Keywords: Wavelength transfer matrix, Arrayed waveguide grating, Ethernet, IP

1. **Introduction.** The explosive growth in data traffic requires increased network transmission capacity because of the introduction of optical transmission technology into communication networks, the increased wireless network speed realized by using innovative wireless broadband connectivity technology, the increased network access caused by the widespread use of devices for accessing the Internet, and the huge data volume related to digital media content, for example high-definition video. According to the Japanese Ministry of Internal Affairs and Communication, broadband traffic is increasing at an annual rate of approximately 30% [1]. This trend is also evident from the fact that broadband service subscriptions in Japan now exceed 20 million because Fiber to the Home (FTTH) has been spreading through the introduction of Passive Optical Networks (PON) into access networks [2]. In a similar trend, Ethernet, which is often used in Local Area Networks (LAN), now employs optical transceivers such as Small Form-factor Pluggable (SFP) and 10 Gigabit Small Form Factor Pluggable (XFP) devices. In recent years, Gigabit Ethernets employing optical communication technologies have been adopted in the data center networks of many companies.

Research has been reported related to the use of Wavelength Division Multiplexing (WDM) [3-5] and the development of network control functions [6-8] in LANs with a view to realizing high performance LANs with a large transmission capacity. On the other hand, a Wide Area Network (WAN) employing an Arrayed Waveguide Grating (AWG) was proposed that could realize a full-mesh wavelength path topology, and this was called an AWG-STAR network [9]. Furthermore, the scalability of the AWG-STAR network was revealed by large-scale field trials in Chitose-city, Hokkaido in Japan [10].

However, the conventional AWG-STAR network had a problem, namely the inefficient use of network transmission capacity, because the wavelength path topology of the AWG-STAR network was fixed but traffic demands fluctuate. Thus, the research has been reported related to an AWG-STAR network with reconfigurable wavelength paths [11]. We have also proposed a novel IP/Ethernet over AWG-STAR network with dynamically relocatable wavelength paths by incorporating a loopback function in a relatively large LAN such as a university campus network to resolve the inefficient consumption of network transmission capacity caused by fluctuating traffic demands [12]. The main difference between the work reported in [11,12] was the method used to realize relocatable wavelength paths. The optical transceivers in [11] could tune the wavelength of the output light. In [12], this function was realized by using optical switches and optical transceivers with fixed wavelengths that were inexpensive and based on the Gigabit Ethernet standards used in the AWG-STAR network. Furthermore, we demonstrated that multiple wavelength paths could be relocated dynamically in the proposed AWG-STAR network [13].

However, wavelength path relocation in the proposed AWG-STAR network complicated the wavelength path topology and made it extremely difficult to manage path relations and network capacity. To solve general complex problem in wavelength routing networks such as a conventional AWG-STAR network, a notation with a wavelength transfer matrix was proposed that could easily express the fixed wavelength path relations among communication nodes [14]. On the other hand, each wavelength path could be relocated with loopback function flexibly and independently in our AWG-STAR network because a specific wavelength output from the AWG could be input to AWG again by optical switches. The notation in [14] could not be directly applied to our AWG-STAR network because it could not express a relocation of a specific wavelength path relocation. So, it was necessary to invent a novel notation that could express relocations of a specific wavelength path.

In this research, we propose a new notation that can express simply the changes in path topology and in network capacity caused by the wavelength path relocation by employing a matrix representation based on [14] to reduce the management load of the network performance of an AWG-STAR network. In Section 2, we explain the wavelength path relocation and network capacity rearrangement, and then we also describe our AWG-STAR network with a loopback function. In Section 3, we propose a new notation for the wavelength path relocation. Furthermore, in Section 4 we show concrete examples that apply the proposed representation to an experimental network constructed by using an 8×8 AWG at our laboratory in order to confirm justification for the proposed matrix representation. Finally, we summarize the results of this research in Section 5.

2. **Wavelength Path Relocation in AWG-STAR Network with Loopback Function.** The advantage of AWG-STAR network with loopback function is that wavelength paths can be relocated dynamically [12]. Figure 1 shows wavelength path relocation. Figure 1 (left) shows the initial full-mesh wavelength path topology in our AWG-STAR network. All of the communication nodes are connected bi-directionally by a one-hop wavelength path. Figure 1 (right) shows the wavelength path topology after relocating some wavelength paths. A new wavelength path is added between nodes 1 and 3 by allocating two unidirectional wavelength paths from node 1 to node 2 and from node 2 to node 3. In the same way, the three unidirectional wavelength paths from node 1 to node 7, from node 7 to node 5, and from node 5 to node 3 are relocated between nodes 1

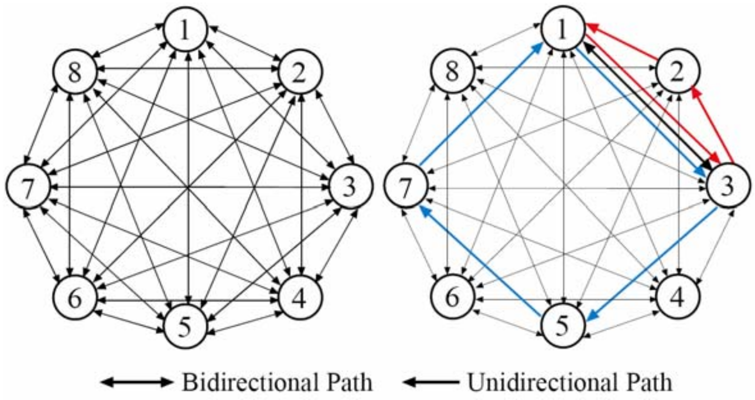

FIGURE 1. Wavelength path relocation in AWG-STAR network with loopback function

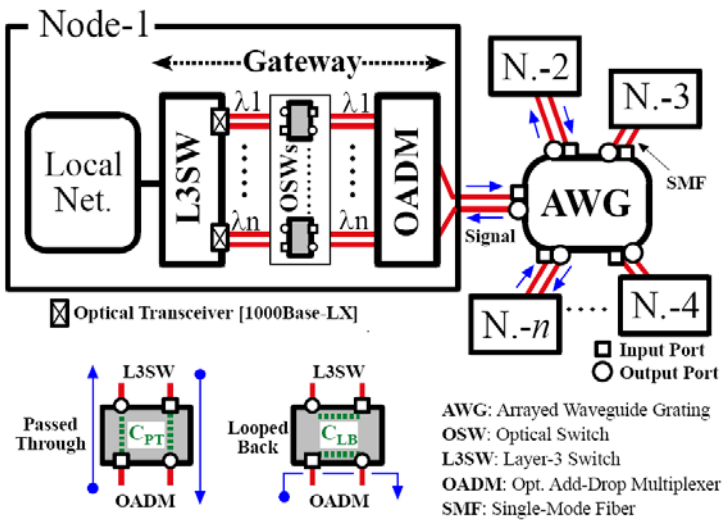

FIGURE 2. Schematic of AWG-STAR network with loopback function

and 3. When traffic demands increase between nodes 1 and 3, wavelength path relocation prevents some congestion and some long delays, and can ensure communication quality because the network transmission capacity increases between nodes 1 and 3. On the other hand, it is necessary to compensate for IP packet transmission by arranging IP packet routing in the IP layer for communication nodes with only a unidirectional path.

Figure 2 shows a schematic of an AWG-STAR network with a loopback function. The $N \times N$ AWG in Figure 2 can route light waves according to wavelength, logically provide wavelength paths with a full mesh topology, and is physically connected to communication nodes by a pair of single mode optical fibers (G.652) with a star topology. Each communication node consists of local networks and a gateway. The local networks communicate with the other nodes through the gateway. The gateway consists of an Optical Add-Drop Multiplexer (OADM) that can multiplex and de-multiplex N wavelengths, N Optical Switches (OSWs) corresponding to each wavelength, and an electrical Layer-3 Switch (L3SW) for Ethernet-switching and IP-routing. Each L3SW is equipped with SFPs that output a specific wavelength. The N signals output from the SFPs are multiplexed into the optical fiber with an OADM, and are input into the AWG. The AWG has a wavelength routing function. The N wavelengths input into one port of the AWG are routed. Then each wavelength is output to a different output port of the AWG, and reaches the destination communication node via the AWG. This is the directional wavelength path between specific communication nodes. The logical network topology formed by the wavelength paths in the optical layer is full-mesh because all the communication nodes are connected directionally by two unidirectional wavelength paths.

Then, we describe the wavelength path relocation that we achieve by changing the states of the OSW in the communication nodes. As shown in Figure 2, at any given time each OSW has one of two states, C_{PT} or C_{LB}. When the state of the OSW is C_{PT}, the optical transceiver (SFP) installed in the L3SW can input an optical signal into the OADM because the SFP is directly connected to the OADM through the OSW. On the other hand, when the state of the OSW is C_{LB}, the wavelength input from the OADM is looped back to the AWG through the OADM because the output port of the OADM is directly connected to the input port of the OADM inside the OSW.

Figure 3 shows the mechanism of wavelength path relocation with a loopback function employing OSWs. When lights (for example, λ_x, λ_y, and λ_z) are launched into input port 1 (InP-1) of the AWG, the lights are output from different output ports (OutPs) thanks to the wavelength routing function, in this case OutP-2: λ_x, OutP-3: λ_y, and OutP-7: λ_z, respectively. When the state of the OSW corresponding to λ_x in communication node 2 is C_{PT}, λ_x is transmitted to the L3SW in node 2. As a result, a unidirectional path for λ_x is constructed from nodes 1 to 3. On the other hand, λ_x can be looped back to InP-2 of the AWG by changing the state of the OSW in node 2 from C_{PT} to C_{LB}. The looped back λ_x is then input into InP-2 and subsequently routed to OutP-3. Finally, it operates as a wavelength path from nodes 1 to 3. This indicates that the wavelength paths from nodes 1 to 2 and from nodes 2 to 3 are relocated to between nodes 1 and 3. The transmission capacity between nodes 1 and 3 is doubled because the wavelength paths from nodes 1 to 3 include λ_x and λ_y. In the same way, λ_z is looped back to InP-7 by the OSW in node 7. And then, λ_z is routed to OutP-5, and is input to InP-5 in the same way that λ_z is looped back in node 5. Finally, λ_z is routed to OutP-3. The wavelength paths from nodes 1 to 7 and from nodes 7 to 5 and from nodes 5 to 3 are relocated between nodes 1 and 3. As a result, the transmission capacity between communication nodes 1 to 3 increases threefold because the wavelength paths from nodes 1 to 3 include λ_x, λ_y and λ_z. In this way, it is

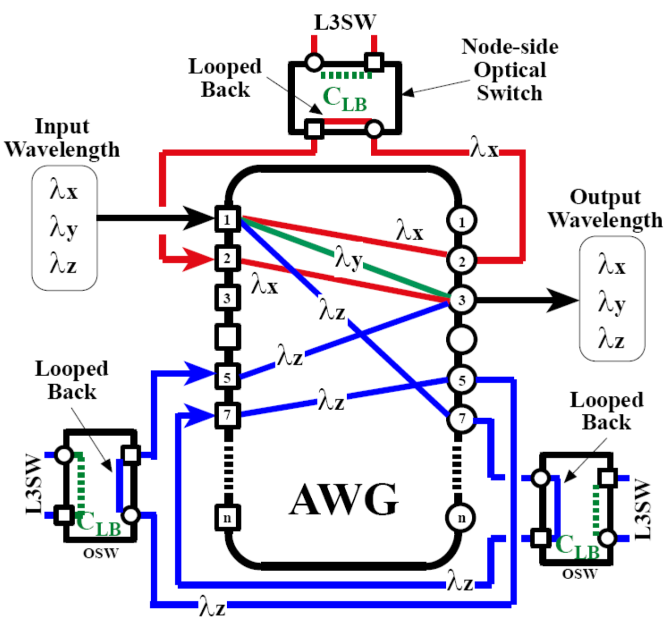

FIGURE 3. Loopback by switching OSWs

possible to allocate an appropriate transmission capacity in response to changes in traffic demand by relocating the wavelength paths among nodes where the traffic demand is relatively low.

3. **Matrix Representation for Wavelength Path Relocation by Loopback Function.** We describe a new notation that can express the wavelength path relation and calculate the change in path topology and network capacity caused by the relocation with a matrix representation based on [14] in an AWG-STAR network with a loopback function. We consider the range including the AWG and the OADM and the OSWs in the communication nodes for a Wavelength Routing Circuit (WRC). The wavelength input-output relationship of the WRC is expressed as Equation (1).

$$O = S \cdot L \cdot I \tag{1}$$

When the number of nodes in the AWG-STAR network is n, the O, S, L and I matrices have n rows and n columns. In addition, the number of wavelengths used in the AWG-STAR network is also n because the wavelength paths are constructed by multiplexing n wavelengths in this research.

I denotes the characteristics of the input wavelength from the nodes to the WRC. Each element $i_{p,q}$ of I is expressed as

$$I = (i_{p,q})_{\substack{p=1,\ldots,n:\ \textit{Node Number} \\ q=1,\ldots,n:\ \textit{Wavelength Number}}} \tag{2}$$

where $i_{p,q}$ is the number of wavelength paths of wavelength q input from node p to WRC.

S denotes the state of an OSW whose element $s_{p,q}$ is expressed as

$$S = (s_{p,q})_{\substack{p=1,\ldots,n:\ \textit{Node Number} \\ q=1,\ldots,n:\ \textit{Wavelength Number}}} \tag{3}$$

where $s_{p,q}$ is the state of an OSW installed in node p to control wavelength q. Shown as Figure 2, when the state of OSW is $\mathrm{C_{PT}}$, $s_{p,q}$ is 0, and when the state of OSW is $\mathrm{C_{LB}}$, $s_{p,q}$ is 1.

O denotes the relation of the connections between nodes with wavelength paths. Each element $o_{j,k}$ is expressed as

$$O = (o_{j,k})_{\substack{j=1,\ldots,n:\ \textit{Transmitting Node Number} \\ k=1,\ldots,n:\ \textit{Receiving Node Number}}} \tag{4}$$

where $o_{j,k}$ is the number of wavelength paths transmitted from node j to node k.

L denotes the wavelength transfer matrix. The rows of L are transmitting nodes, and the columns of L are receiving nodes. The element Λ_r of L indicates a wavelength routed by the routing function of the AWG. The AWG in this research has a cyclic characteristic. Therefore, L and each element is expressed as

$$L = \begin{pmatrix} \Lambda_1 & \Lambda_2 & \Lambda_3 & \cdots & \Lambda_r & \cdots & \Lambda_n \\ \Lambda_n & \Lambda_1 & \Lambda_2 & \cdots & \Lambda_{r-1} & \cdots & \Lambda_{n-1} \\ \Lambda_{n-1} & \Lambda_n & \Lambda_1 & \cdots & \Lambda_{r-2} & \cdots & \Lambda_{n-2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \Lambda_2 & \Lambda_3 & \Lambda_4 & \cdots & \Lambda_{r+1} & \cdots & \Lambda_1 \end{pmatrix}_{r=1,2,\ldots,n} \tag{5}$$

where r is the element number of L.

Then, we show a calculation that can express the changes in path topology and network capacity caused by wavelength path relocation. Prior to the calculation, it is necessary to confirm whether the relationship between I and S is contradictory. In particular, when the state of the OSW corresponding to wavelength q in node p is $\mathrm{C_{LB}}$, the signal of wavelength q transmitted from L3SW in node p is looped back through the OSW, and wavelength q is not input into the WRC. Thus, the matrix element $i_{p,q}$ of I must be 0. For this confirmation, we find the detection matrix D shown as

$$D = I \circ S = (d_{p,q}) \begin{array}{l} p = 1, \ldots, n: \ \textit{Node Number} \\ q = 1, \ldots, n: \ \textit{Wavelength Number} \end{array} \tag{6}$$

where matrix elements $d_{p,q}$ are determined by multiplying $i_{p,q}$ and $s_{p,q}$. When $d_{p,q}$ is not 0, we can find that the signal of wavelength q in node p is not input into the WRC because it is looped back to L3SW. Until D becomes a zero matrix, all $i_{p,q}$ corresponding to $d_{p,q} \neq 0$ are changed to 0. Next, we show a calculation procedure that can express the changes in path topology and network capacity that result from wavelength path relocation. The calculation is performed for a matrix corresponding to each wavelength. First, we find I_q, S_q and L_q included in I, S and L, respectively. We solve O_q corresponding to wavelength q, and finally calculate O in Equation (1) by totaling all the O_q values.

First, we calculate I_q from I. I_q corresponding to wavelength q is expressed as

$$I_q = diag\,(i_{1,q}, i_{2,q}, \cdots, i_{n,q}) \tag{7}$$

Equation (7) indicates I_q which is made by converting each diagonal element of an identity matrix (n rows and n columns) into each element $i_{p,q}$ of the column corresponding to wavelength q of I. In the same way, each L_q based on L is calculated. L_q corresponding to wavelength q is expressed as

$$L_q = (l_{j,k}) \begin{array}{l} j = 1, \ldots, n: \ \textit{Transmitting Node Number} \\ k = 1, \ldots, n: \ \textit{Receiving Node Number} \end{array} \tag{8}$$

The element $l_{j,k}$ of L_q is 1 when the wavelength q and the element number r match. On the other hand, $l_{j,k}$ is 0, shown as

$$l_{j,k} = \begin{cases} 1, & q = r \\ 0, & q \neq r \end{cases} \tag{9}$$

The OSW state matrix S_q is expressed as

$$S_q = (t_{j,k}) \tag{10}$$

The matrix element $t_{j,k}$ is expressed as

$$t_{j,k} = \begin{cases} e_{m,j}, & s_{p,q} = 0 \\ l_{j,m}, & s_{p,q} = 1 \end{cases}, \quad m = 1, 2, \ldots, n \tag{11}$$

Equation (11) indicates that the m-th column of S_q is equal to the m-th column of the identity matrix when the state of the OSW corresponding to wavelength q in node m is $\mathrm{C_{PT}}$. On the other hand, Equation (11) shows that the m-th column of S_q is equal to the m-th row of L_q when the state of the OSW is $\mathrm{C_{LB}}$.

O_q corresponding to wavelength q is expressed as

$$O_q = (o_{j,k}) \begin{array}{l} j = 1, \ldots, n: \ \textit{Transmitting Node Number} \\ k = 1, \ldots, n: \ \textit{Receiving Node Number} \end{array} \tag{12}$$

O_q is calculated as

$$O_q = \left(S_q^z \cdot (L_q)^T \cdot I_q \right)^T \tag{13}$$

where z is the loopback number and S_q^z is the identity matrix if z is 0. In addition, T shows the operation of matrix transposition. After obtaining O_q for all wavelengths, O is calculated as

$$O = \sum_{q=1}^{n} O_q \tag{14}$$

where the element $o_{j,k}$ in O shows the path topology of the AWG-STAR network, and the numerical value of $o_{j,k}$ shows the traffic capacity between nodes j and k. For example, when SFP is used as an optical transceiver in L3SW and $o_{j,k}$ is 1, the traffic capacity is 1 Gbps. Similarly, when $o_{j,k}$ is 2, it is 2 Gbps.

4. **Matrix Representation for Wavelength Path Relocation in Experimental Network.** This section describes two concrete examples that employ the proposed matrix representation. We actually constructed the proposed AWG-STAR network experimentally in our laboratory by using an 8×8 AWG [13]. Table 1 shows the wavelength routing characteristics of the 8×8 AWG. In the initial state, it was assumed that the communication nodes were logically connected wavelength paths with a full-mesh topology as shown in Figure 1 (left).

TABLE 1. Wavelength routing characteristic

AWG Port	Out P1	Out P2	Out P3	Out P4	Out P5	Out P6	Out P7	Out P8
In P1	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8
In P2	λ_8	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
In P3	λ_7	λ_8	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6
In P4	λ_6	λ_7	λ_8	λ_1	λ_2	λ_3	λ_4	λ_5
In P5	λ_5	λ_6	λ_7	λ_8	λ_1	λ_2	λ_3	λ_4
In P6	λ_4	λ_5	λ_6	λ_7	λ_8	λ_1	λ_2	λ_3
In P7	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	λ_1	λ_2
In P8	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	λ_1

For first example, we made some changes to the wavelength path topology and network capacity of the network by switching the state of the OSW corresponding to λ_2 in node 2 and the states of the OSWs corresponding to λ_5 in nodes 5 and 7 from C_{PT} to C_{LB}. Furthermore, second example gave some changes the states of the OSWs corresponding to λ_2 in nodes 2, 3, 4, 5, 6 and 7 from C_{PT} to C_{LB}.

At first, we expressed the initial state as a full-mesh path topology in the experimental network with the proposed matrix representation. The wavelength transfer matrix L was expressed as

$$L = \begin{pmatrix} \Lambda_1 & \Lambda_2 & \Lambda_3 & \Lambda_4 & \Lambda_5 & \Lambda_6 & \Lambda_7 & \Lambda_8 \\ \Lambda_8 & \Lambda_1 & \Lambda_2 & \Lambda_3 & \Lambda_4 & \Lambda_5 & \Lambda_6 & \Lambda_7 \\ \Lambda_7 & \Lambda_8 & \Lambda_1 & \Lambda_2 & \Lambda_3 & \Lambda_4 & \Lambda_5 & \Lambda_6 \\ \Lambda_6 & \Lambda_7 & \Lambda_8 & \Lambda_1 & \Lambda_2 & \Lambda_3 & \Lambda_4 & \Lambda_5 \\ \Lambda_5 & \Lambda_6 & \Lambda_7 & \Lambda_8 & \Lambda_1 & \Lambda_2 & \Lambda_3 & \Lambda_4 \\ \Lambda_4 & \Lambda_5 & \Lambda_6 & \Lambda_7 & \Lambda_8 & \Lambda_1 & \Lambda_2 & \Lambda_3 \\ \Lambda_3 & \Lambda_4 & \Lambda_5 & \Lambda_6 & \Lambda_7 & \Lambda_8 & \Lambda_1 & \Lambda_2 \\ \Lambda_2 & \Lambda_3 & \Lambda_4 & \Lambda_5 & \Lambda_6 & \Lambda_7 & \Lambda_8 & \Lambda_1 \end{pmatrix}.$$

Since eight wavelengths were input from all the nodes into a WRC initially, the input matrix I was expressed, and the OSW state matrix S was expressed as follows, because all of the OSWs were C_{PT}.

$$I = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}, \quad S = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

Therefore, the detection matrix D was a zero matrix. So, we could move on to the next step. Here, we considered λ_2. The I_2, L_2 and S_2 matrices were expressed as follows, respectively.

$$I_2 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \quad L_2 = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix},$$

$$S_2 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$$

Thus, O_2 corresponding to λ_2 was expressed as

$$O_2 = \left(S_2^z \cdot (L_2)^T \cdot I_2\right) = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix},$$

where z was 0 because the loopback number was 0. We also performed the calculation for other wavelengths. Thus, O was expressed as

$$O = \sum_{q=1}^{8} O_q = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}.$$

As a result, we found that the communication nodes were logically connected wavelength paths with a full-mesh topology.

Then, we show the first example matrix representation for wavelength path relocation. When the states of the OSWs corresponding to λ_2 in node 2 and corresponding to λ_5 in nodes 5 and 7 from C_{PT} to C_{LB} were changed, S was expressed, and D was expressed as follows, respectively.

$$S = \begin{pmatrix} 0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0 \end{pmatrix}, \quad D = \begin{pmatrix} 0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0 \end{pmatrix}.$$

In this case, we found that the wavelengths λ_2 in node 2 and λ_7 in nodes 5 and 7 were not input into the WRC. Therefore, we stopped transmitting the signals corresponding to λ_2 in node 2 and λ_7 in nodes 5 and 7. Thus, I was expressed as

$$I = \begin{pmatrix} 1&1&1&1&1&1&1&1 \\ 1&0&1&1&1&1&1&1 \\ 1&1&1&1&1&1&1&1 \\ 1&1&1&1&1&1&1&1 \\ 1&1&1&1&1&1&0&1 \\ 1&1&1&1&1&1&1&1 \\ 1&1&1&1&1&1&0&1 \\ 1&1&1&1&1&1&1&1 \end{pmatrix}.$$

Because the detection matrix D was 0, we could move on to the next calculation. Here, we considered λ_7. The I_7, L_7 and S_7 matrices were expressed as follows, respectively.

$$I_7 = \begin{pmatrix} 1&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&1 \end{pmatrix}, \quad L_7 = \begin{pmatrix} 0&0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&1 \\ 1&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \end{pmatrix},$$

$$S_7 = \begin{pmatrix} 1&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \\ 0&0&1&0&1&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&1 \end{pmatrix}.$$

Thus, O_7 corresponding to wavelength 7 was expressed as

$$O_7 = \left(S_7^2 \cdot (L_7)^T \cdot I_7 \right) = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix},$$

where z was 2 since the loopback number was 2. We also performed the calculation for other wavelengths. Thus, O was calculated as Equation (15).

$$O = \sum_{q=1}^{8} O_q = \begin{pmatrix} 1 & 0 & 3 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}. \tag{15}$$

As a result, we found that the wavelength paths from nodes 1 to 7, from nodes 7 to 5, and from nodes 5 to 3 were relocated to the wavelength path from nodes 1 to 3 as shown in Figure 1 (right) and that the number of wavelength paths was increased threefold. As a result, the transmission capacity between communication nodes 1 to 3 also increased threefold.

We show the justification on the result of the first example. As shown in Table 1, the wavelength path corresponding to λ_2 in node 1 was input into InP-1 in the AWG, and then it was output from OutP-2. However, it was looped back to InP-2 in the AWG through the OSW corresponding to λ_2 in node 2 because the state of the OSW was C_{LB}. The looped back wavelength λ_2 was then input into InP-2, and routed to OutP-3 subsequently. Thus, the connections among nodes corresponding to λ_2 were shown in Figure 4 (left). Similarly, Figure 4 (right) showed the connection corresponding to λ_7. Figure 1 (right) showed the wavelength path topology including all wavelength paths in first example. We found that the proposed matrix representation was correct because the value of the matrix element (row 1, column 3) in Equation (15) was equal to the number of wavelength path from nodes 1 to 3 shown in Figure 1 (right). Furthermore, there were not wavelength paths corresponding to λ_2 from nodes 1 to 2, from nodes 2 to 3. And there also were not wavelength paths corresponding to λ_7 from nodes 3 to 5, from nodes 5 to 7 and from nodes 7 to 1 in Figure 1 (right). It was confirmed that the elements which were 0 in Equation (15) agreed with the relationship which did not have any wavelength path among the nodes.

In second sample, we considered a situation where the states of the OSWs correspond to λ_2 in nodes 2, 3, 4, 5, 6 and 7 from C_{PT} to C_{LB}. In a similar way to previous example,

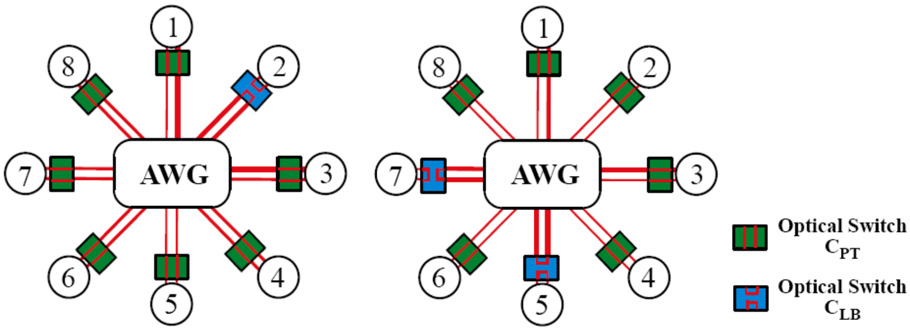

FIGURE 4. Wavelength paths among nodes corresponding to λ_2 and λ_7

O_2 corresponding to λ_2 was derived as the following

$$O_2 = \left(S_2^z \cdot (L_2)^T \cdot I_2\right) = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix},$$

where z was 6 because the loopback number was 6. We also performed the calculation for other wavelengths. Thus, O was calculated as Equation (16).

$$O = \sum_{q=1}^{8} O_q = \begin{pmatrix} 1 & 0 & 1 & 1 & 1 & 1 & 1 & 2 \\ 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}. \tag{16}$$

We found that the wavelength paths from nodes 1 to 2, from nodes 2 to 3, from nodes 3 to 4, from nodes 4 to 5, from nodes 5 to 6, from nodes 6 to 7 and from nodes 7 to 8 were integrated. The integrated wavelength path became a wavelength path from nodes 1 to 8. As a result, the transmission capacity between communication nodes 1 to 8 doubled.

The wavelength path corresponding to λ_2 in node 1 was input into InP-1 in the AWG, and then, it was output from OutP-2 as shown in Table 1. However, it was looped back to InP-2 in the AWG through the OSW in node 2. The looped back wavelength was then input into InP-2 and subsequently routed to OutP-3. The looping back was conducted five times additionally in nodes 3, 4, 5, 6 and 7. Finally, the wavelength path was transmitted to node 8. Thus, the wavelength paths corresponding to λ_2 were shown in Figure 5 (left). Figure 5 (right) showed the derived topology including all wavelength paths in the second example. We also confirmed that the derived result shown in Equation (16) agreed with the wavelength path relationships among nodes in Figure 5 (right).

Consequently, we could express the wavelength path topology in the AWG-STAR network with loopback function employing an 8×8 AWG with the proposed matrix representation, and showed that the changes in path topology and in network capacity caused by the relocations could be derived. Furthermore, the matrix representation can apply to

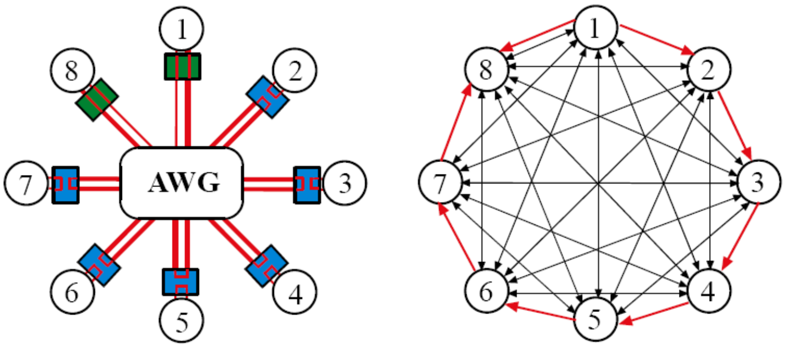

FIGURE 5. Wavelength paths among nodes corresponding to λ_2, and wavelength path topology

the AWG-STAR network with loopback function, employing $N \times N$ AWG and N optical switches in each node flexibly.

5. **Conclusion.** We proposed a new matrix representation that could express some changes in path topology and in network capacity caused by relocating wavelength paths in the AWG-STAR network with loopback function. Furthermore, we showed concrete examples in which the proposed matrix representation could be applied to the experimental network employing an 8×8 AWG. This representation was effective in reducing management loads for the extremely complex network performance and path relations among communication nodes. In future work, the proposed matrix representation will be innovated to a network management system [8] in order to realize automatic relocation and reduce the management load of the network performance of the AWG-STAR network with loopback function.

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