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User selective mode-forming remote switch in multi-mode fiber distributing networks using MIMO processing

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ABSTRACT

A mode-forming remote switch in multi-mode fiber distributing networks has been proposed. It can transmit the desired data to the desired port by adjusting transmitter signals. Feasibilities of the proposed scheme are confirmed by switching sub-carrier BPSK signal to the selected port. A graded-index multi-mode fiber link whose output is divided into two ports by a mode-dependent optical coupler, is used as mode-division multiplexing network. Its channel matrix is obtained by using MIMO processing technologies. Amplitudes and phases of the data are adjusted according to the channel matrix. The data is successfully switched to the desired port. Also, wavelength independences are clarified.

1. Introduction

In recent years, passive optical network (PON) technology is growing rapidly in order to reduce overall costs and expand service areas [1]. Wavelength division multiplexing (WDM) is an effective method to enhance transmission capacity including extending reach. However, wavelength independence is preferable for future scalabilities and cost. Recently, there are some new PON architectures employing hybrid optical distribution networks (ODN), such as hybrid mode division multiplexing (MDM) and optical code division multiplexing (OCDM) systems [2], and hybrid MDM-time division multiplexing (TDM) systems [3], both utilizing MDM. These PON architectures utilize multi-mode fiber (MMF) or few-mode fiber (FMF) as MDM transmission media. On the other hand, due to the spread of the number of internet users, security issues have emerged. Usually, important signals to be transmitted can be encrypted, but the encrypted signals are sometimes deciphered or eavesdropped by others. High security networks are required to prevent unauthorized access, especially in passive optical access networks which distribute optical signals to many optical networks units (ONUs) [4,5]. Therefore, a lossless remote controlled switch was proposed to transmit the desired data to the desired user by using time reversal array transmitter techniques as a wavelength independent passive switching method for point-to-multipoint networks [6]. Time-reversal method requires extremely low propagation time differences within transmission paths because it utilizes optical carriers.

In this paper, we propose mode-forming networks which are constructed by MDM multi-mode fiber (MMF) networks. Feasibilities of the proposed scheme are confirmed by the 2 output port distribution MMF networks. The proposed scheme uses sub-carrier multiplexing (SCM) techniques. Amplitude and phase controlled data are transmitted by the different transmitters and the output port is selected by adjusting the transmitter data. The data can be successfully switched to the desired port. Also, the wavelength independences of the light source are discussed.

2. Principle of mode-forming remote switch

The basic concept of our proposed mode-forming networks is shown in Fig. 1(a), schematically. Mode-forming networks consist of transmitters (Txs) which can transmit different superimposed data indicating different colors, MDM transmission media such as MMF or Few-mode fiber (FMF), and receivers (Rx). The relation of data, transmitter signals and received signals are shown in Fig. 1(b). Transmitter signals are combined with different data and propagate different path inside MMF experiencing different loss and delay. Therefore, only the desired signal can be received by *Rx i* while other transmitter signals are cancelled by controlling the phases and amplitudes of the transmitter signals. This scheme is almost the same as the time reversal method [6]. This method was realized using Polarization maintaining (PM) fiber. We propose to use microwave sub-carrier signals instead of optical carriers to achieve stable operation. The proposed method is independent of signal types, such as data rate, modulation format and so on.

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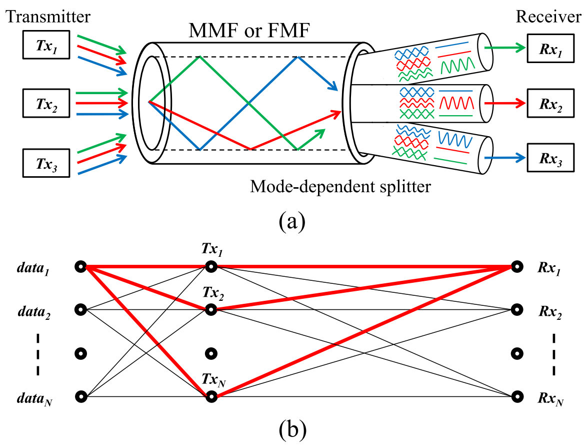

Fig. 1. Basic concept of mode-forming networks. (a) Different colors indicate different data with the same wavelength, each transmitter (Tx) sends superimposed data and propagates in the multi-mode fiber. (b) Details path of (a). Data are at left, transmitters are in the center, and receivers are on the right. One path from $data_1$ to Rx1 is shown in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The mode-forming network functions as remote switch that can select an output port by controlling transmitter signals [7] and networks, which can transmit an arbitrary output port simultaneously. In this research, a remote switch function is demonstrated.

To realize the proposed method, transmitter signals, which consist of superimposed data, need to be clarified. The transmission characteristics of the MMF network shown in Fig. 2(a) can be expressed as

$$\boldsymbol{y} = \boldsymbol{Hx} \tag{1}$$

where $\boldsymbol{H}$ is the channel matrix which represents MMF characteristics, $\boldsymbol{y} = [y_1, y_2,\ldots,y_N]^T$ and $\boldsymbol{x} = [x_1, x_2,\ldots,x_N]^T$ are the vector of received signals and transmitter signals, respectively. N is the number of transmitters or receivers, and $[]^T$ denotes the transpose matrix.

The transmitter signal $\boldsymbol{x}$ in Fig. 2(b) can be expressed as

$$\boldsymbol{x} = \boldsymbol{wd} \tag{2}$$

where $\boldsymbol{w}$ is the weight matrix and $\boldsymbol{d} = [d_1, d_2,\ldots,d_N]^T$ is the input data. The received signal $\boldsymbol{y}$ in Fig. 2(b) can be expressed as

$$\boldsymbol{y} = \boldsymbol{Hx} = \boldsymbol{Hwd} \tag{3}$$

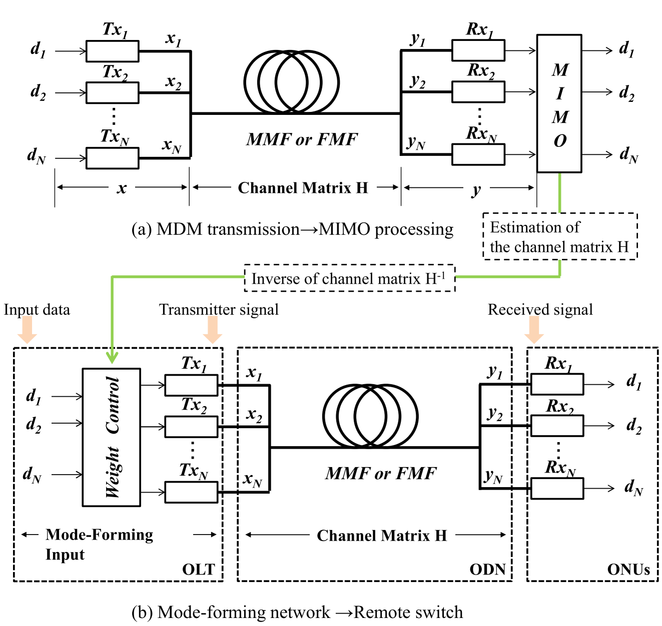

Fig. 2. Configuration of the proposed mode-forming networks (b) by utilizing MIMO processing (a).

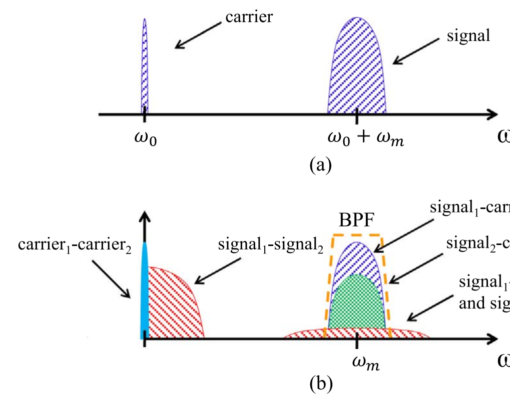

Fig. 3. Principle of SCM-SS transmission for MDM transmission networks. $\omega_0(=c/\lambda)$ is the optical carrier frequency, ω_m is the subcarrier frequency. Signal from Channel1. Signal from Channel2. Impairment. DC component. (a) Optical spectrum create by SCM. (b) Electrical spectrum with spread spectrum.

If the received signal $\boldsymbol{y}$ is equal to $\boldsymbol{d}$, $\boldsymbol{HW} = \boldsymbol{E}$ should be the identity matrix. As a result, the matrix $\boldsymbol{w}$ should be the inverse of the channel matrix as

$$\boldsymbol{w} = \boldsymbol{H}^{-1} \tag{4}$$

These results indicate that if the input signals are produced by the linear combination of the input data, the input signals can be divided at the desired output port.

To realize the proposed remote switch, received signals should consist of a linear combination of transmitter signals. The proposed scheme uses single-sideband sub-carrier multiplexing (SCM) techniques instead of coherent transmission systems. The optical spectrum created by two channel SCM signals is schematically shown in Fig. 3(a). When the two signals are transmitted simultaneously, the detected signal of the photo detectors is shown in Fig. 3(b). There are many electrical frequency components, that is, signal-carrier, signal-signal and carrier-carrier with the same signals or different signals. Components signal-signal and carrier-carrier can be rejected by electrical band-pass filter. But, the components of signal-carrier which are interferences between two signals can't be rejected. To eliminate the influence, a spread spectrum (SS) technique is applied [8]. However, if the wavelength of the light sources is different and the frequency difference is out of the electrical bandwidth, the influences can be ignored. Therefore, if the SCM system is used, these interfered signals can be recovered by MIMO processing techniques used in wireless communications.

3. Mode-forming remote switch

The procedure of the proposed mode-forming remote switch is clarified for a 2 channel mode-forming network. To clarify the requirement for the weight matrix, the elements for the weight matrix are obtained. The weight matrix is assumed as

$$\boldsymbol{w} = \begin{pmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \end{pmatrix} \tag{5}$$

Then, the received signal $\boldsymbol{y}$ is expressed as

$$\boldsymbol{y} = \boldsymbol{Hwd} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix}\begin{pmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \end{pmatrix}\begin{pmatrix} d_1 \\ d_2 \end{pmatrix} \tag{6}$$

Eq. (6) can be expressed as

$$\boldsymbol{y} = \begin{pmatrix} (h_{11}w_{11} + h_{12}w_{21})d_1 + (h_{11}w_{12} + h_{12}w_{22})d_2 \\ (h_{21}w_{11} + h_{22}w_{21})d_1 + (h_{21}w_{12} + h_{22}w_{22})d_2 \end{pmatrix} \tag{7}$$

When only d_1 (d_2=0) is inputted and the output should be at the $Rx1$ port, the coefficient of the $Rx2$ output port should be zero, that is