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Performance analysis of fiber optical wide area network using SDM/WDM router

Lan-Chih Yang, Chien-Chang Huang*

Department of Communication Engineering, Yuan Ze University, Taoyuan, Taiwan

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ABSTRACT

A spatial division multiplexing/wavelength division multiplexing (SDM/WDM) router has been designed for a fiber optical wide area network (WAN). The router includes a 32 × 32 optical switch and eight 1 × 4 demultiplexers (DeMUXs) and eight 4 × 1 multiplexers (MUXs). The system performances for various spans and transmission speeds are simulated and compared with the results of analytical calculations. Both the $LiNbO_3$ and semiconductor optical amplifier (SOA) switches for the dilated Benes switch configuration are studied. The simulation results show that the SDM/WDM WAN using the SOA based router performs better than the $LiNbO_3$.

1. Introduction

Array waveguide routers (AWR) for applications in wavelength division multiplexing (WDM) optical fiber communication networks have received significant attention recently [1–9]. The schematic diagram of the traditional WDM AWR is shown in Fig. 1(a). However, as the channel number increases, the size of array waveguide grating (AWG) becomes too large, that may reduce the production yield and increase the manufacturing cost. Moreover, as the number of wavelengths increases in a single mode fiber (SMF), the nonlinear effects become more severe [10] including four-wave mixing [11], cross-phase modulation [12], self-phase modulation, stimulated Raman scattering [13,14], and stimulated Brillouin scattering [15]. These nonlinear effects degrade the network performance that is difficult to recover by changing other system parameters. Therefore, reducing the wavelength numbers in an SMF is an easy and practical way for the actual fiber network design.

But, how to keep the same capacity with less wavelength numbers in a fiber-optical wide area network (WAN)? The spatial division multiplexing (SDM) would be a good solution. In this paper, we propose an SDM/WDM router using eight 1 × 4 demultiplexers (DeMUXs) and eight 4 × 1 multiplexers (MUXs) as shown in Fig. 1(b). The reason we adopt eight 1 × 4 DeMUX and eight 4 × 1 MUX is that the two elements are the most popular WDM components with low cost and easy for mass production using both of AWG technology and thin film filter technology.

Up to now, the $LiNbO_3$ switches are the commercially available product in the fiber optical communications market. The optical crossconnect (OXC) using $LiNbO_3$ switches for add/drop has been reported [16]. Although other switches using semiconductor optical amplifier (SOA) are not yet commercialized, several studies have been carried out to show their performance improvement. The OXC optical add-drop multiplexer (OADM) using SOA switches were also reported with a promising potential [17]. In this paper, two optical switches – $LiNbO_3$ switches and SOA switches – are examined for a 32 × 32 optical switch in the proposed SDM/WDM router. The dilated Benes [18] optical switch configuration is used for designing the 32 × 32 optical switch. The schematic diagram of the designed optical network using SDM/WDM router with $LiNbO_3$ or SOA switches is shown in Fig. 2 where the filters enclosed by slash lines are used only with the SOA switches.

Although the fiber span in WAN is about 40–120 km, the dispersion effect degrades the system performance, especially for high data rate transmissions. The dispersion management has been demonstrated to improve the dispersion effect in a long distance fiber transmission system [19]. Therefore, a fiber network with positive and negative dispersion coefficients before and after the SDM/WDM router is considered in this paper for future higher speed WAN.

The remainder of this paper is organized as follows: Section 2 describes the mathematical formulation of the switching network performance with bit-error-rate (BER) analysis. The dilated Benes switching networks based on $LiNbO_3$ and SOA switches are analyzed and simulated in Section 3. Finally, some concluding remarks are provided in Section 4.

2. BER formulations for switching networks

In this paper, we use the software package LinkSIM [20]. Comparisons have also been made with analytic calculations by MATLAB

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* Corresponding author. Tel.: +886 3 4638800x7315; fax: +886 3 4554264.
E-mail address: cch@saturn.yzu.edu.tw (C.-C. Huang).

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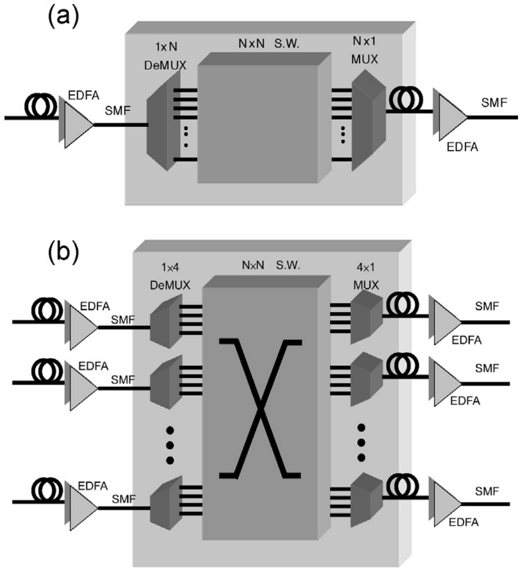

Fig. 1. Schematics of (a) traditional WDM AWR and (b) proposed SDM/WDM AWR.

for the performance evaluations of the designed SDM/WDM router. The basic BER expression can be described as [21]

$$\mathrm{BER} = \frac{1}{2} erfc\left(\frac{\rho}{\sqrt{2}}\right) \tag{1}$$

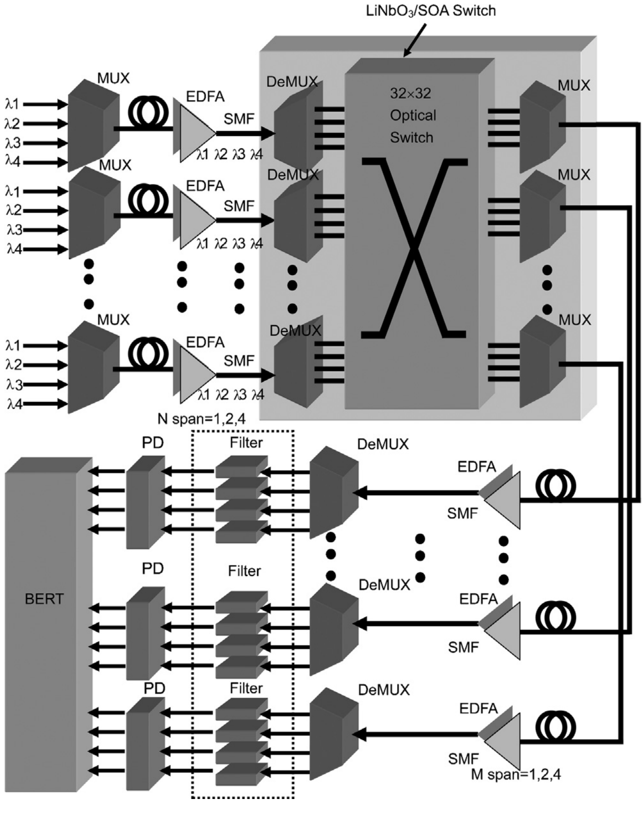

Fig. 2. Schematic of designed optical networks using SDM/WDM router with LiNbO$_3$/SOA switch.

where *erfc*( ) is the complementary error function and the parameter ρ represents the signal-to-noise-ratio (SNR) without crosstalk effects expressed as

$$\rho = \frac{2S}{\sqrt{\sigma_s^2 + \sigma_t^2 + \sigma_{lw}^2 + \sigma_{sig=ASE}^2 + \sigma_{ASE=ASE}^2}} = \frac{2S}{\sigma_{eff}}. \tag{2}$$

In (2), S is the received-signal amplitude with the expression of $S = R \cdot M \cdot P_s$; R is the receiver responsivity, M is the multiplication factor of avalanche photodiodes (APDs), P_s is the signal power. For the noise terms, σ_s^2 is the shot noise, σ_{lw}^2 is the noise from the laser diode (LD) linewidth, σ_t^2 is the thermal noise, $\sigma_{sig=ASE}^2$ is the noise power due to the interaction of signal and amplified spontaneous emission (ASE) noise, $\sigma_{ASE=ASE}^2$ is the noise power due to ASE alone, and σ_{eff}^2 represents the effective amplitude of noise. The details for the noise factors are [22,23]

$$R = \frac{\eta q}{h\nu} \tag{3}$$

$$\sigma_s^2 = 2q(RM^{(2+x)})\Delta B P_r \tag{4}$$

$$\sigma_t^2 = \frac{4k_B FT}{R_L}\Delta B \tag{5}$$

$$\sigma_{lw}^2 = K^2 \Delta\nu \Delta B \tag{6}$$

$$\sigma_{sig=ASE}^2 = 4R^2 G P_s S_{ASE} \Delta B \tag{7}$$

$$\sigma_{ASE=ASE}^2 = 4R^2 S_{ASE}^2 \Delta\nu_{opt} \Delta B \tag{8}$$

$$S_{ASE} = (G-1) n_{sp} X h\nu \tag{9}$$

where q is the electron charge, x is the excess noise factor of the APD, ΔB is the electrical bandwidth, P_r is the received signal power, η is the quantum efficiency of the photodiode, $h\nu$ is the photon energy, k_B is the Boltzmann constant, F is the receiver noise figure, T is the absolute temperature, R_L is the load resistance, K is the conversion efficiency, $\Delta\nu$ is the linewidth of LD, G is the optical amplifier gain, P_s is the signal power, S_{ASE} is the spontaneous emission spectral density, n_{sp} is the population-inversion parameter, X is a factor used to account for the nonuniform carrier density distribution due to gain saturation, and $\Delta\nu_{opt}$ is the optical filter bandwidth.

In the case of WDM transmission, the interchannel-interference due to crosstalk must also be considered for BER evaluations. The joint probability density function (PDF) can be utilized for the interferences that are treated as a receiver noise. With such equivalence of interferences, the BER expression can be modified as [21]

$$\mathrm{BER} = \frac{1}{2^N}\sum_{i=0}^{2^N-1} erfc\left(\frac{\rho_i}{\sqrt{2}}\right) \tag{10}$$

with

$$\rho_i = \frac{1}{e_{eff}}\left(S + \sum_{j=1}^{N-1} w_{ij} a_j\right) \tag{11}$$

where i and j denote the state of interferences and the number of interference channels, respectively; w_{ij} is +1 for “mark” and is −1 for “space”, and a_j is the amplitude PDF for the interference symbol. Taking a 3-channel transmission system as an example, the BER can be written as

$$\mathrm{BER} = \frac{1}{8}\left\{erfc\left(\frac{\rho_{111}}{\sqrt{2}}\right) + erfc\left(\frac{\rho_{110}}{\sqrt{2}}\right) + erfc\left(\frac{\rho_{101}}{\sqrt{2}}\right) + erfc\left(\frac{\rho_{100}}{\sqrt{2}}\right)\right\} \tag{12}$$

with

$$\rho_{111} = \frac{S + a_1 + a_2}{\sigma_{eff}} \tag{13}$$