Power Penalty of Ultrafast Time-Division Demultiplexer using Cascaded Multi-Quantum Well Electro-absorption Modulators

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Abstract—We have studied a novel approach using several cascaded multi-quantum well electro-absorption (MQW-EA) modulators to achieve ultrafast time-division demultiplexing. The major advantage is that the bandwidth requirement of the modulators can be greatly reduced. We have studied the power penalty due to the extinction ratio and the absorption characteristics of the MQW-EA modulators in an optically amplified system using this kind of demultiplexer. The results show that the system performance greatly depends on these two parameters and thus are important in the demultiplexer design.

I. INTRODUCTION

Recently, ultrahigh-speed all-optical time division multiplexed (TDM) systems are of great interest. System bit rate as high as 200 Gbit/s has been demonstrated [1]. One of the key functions of such ultrahigh-speed optical transmission systems is to demultiplex a specific channel and extract the information carried by that channel. This requires time-division demultiplexers with very fast response time, usually in the order of subpicosecond, for use in such ultrahigh-speed systems. This high bandwidth requirement of the components makes the system very expensive. Thus, it is very desirable to have some schemes that can relax the component's bandwidth requirement but still can perform ultrafast demultiplexing. Some of the ultrafast time-division demultiplexers [2], such as nonlinear optical loop mirrors (NOLM), optical Kerr switches, are realized by utilizing the nonlinearities. In [3], it has been reported that ultrafast time-division demultiplexing can also be achieved by using the cascaded optical modulators switches, which have the advantage of increasing the demultiplexing rate without increasing the bandwidth of the optical modulators and the related electronics. Moreover, such simple configuration is suitable for monolithic integration [4]. In this paper, we study the power penalty due to the extinction ratio and the absorption characteristics of the multi-quantum well electro-absorption (MQW-EA) modulators in a cascaded configuration as an ultrafast time division demultiplexer.

II. CASCaded MQW-EA MODULATORS

Figure 1 shows the system configuration. Each stage of the demultiplexer consists of two MQW-EA modulators cascaded in series with a $\frac{\pi}{2}$ phase difference in their control voltages which are biased at zero-voltage point. The resultant modulation waveforms are shown in Figure 2. In this way, an $M$ bit/s pulse stream can be demultiplexed into an $M/2$ bit/s pulse stream by a single stage of cascaded modulators with $M/4$ Hz control signals. For each MQW-EA modulator, the modulation characteristics can be expressed as [3,4]:

$$T_{MQW} = p + (1 - p) \exp \left\{ (-V/V_o)^q \right\} \quad (1)$$

where $V$ is the applied voltage, $V_o$ is a voltage constant, $q$ is the absorption parameter and $p$ is the saturated output for unit device length. Note that $p$ controls the modulator's extinction ratio which is defined as the ratio of the maximum to minimum power output of the modulator. Figure 3 shows the modulation waveform of a single MQW-EA modulator with a sinusoidal control voltage and different values of $q$ which control the
steepness of the absorption change [4]. The value of \( q \) can be increased by using a longer device [5] and this makes the modulation waveform become more square than sinusoidal. We have found that \( q \) should be a positive even integer in order to attain the desired modulation waveform in the cascaded configuration as shown in Figure 2. Thus, we rewrite expression \( 1 \) as:

\[
T_{MQW} = p + (1 - p) \left\{ \exp\left( -\frac{V}{V_o} \right)^{2q'} \right\}
\]

where \( q' \) is a positive integer. Consider a 4-stage cascaded MQW-EA modulators to demultiplex a \( M/16 \) bit/s data stream from a \( M \) bit/s multiplexed data stream. The applied control voltages to the modulators are \( M/2^{(i+1)} \) Hz at the \( i \) th stage. The resultant modulation waveform is shown in Figure 4 and this can be regarded as the demultiplexing profile. From Figure 4, the side peaks will take out some power from the adjacent channels and lead to noise contribution to this demultiplexed bit period during detection. This situation is even more severe in optically-amplified system since the amplified-spontaneous emission (ASE) noise in the adjacent channels will lead to considerable noise accumulation at the receiver and degrade the receiver sensitivity. The demultiplexing profile actually depends greatly on the extinction ratio of the modulators. Better modulators' extinction ratio gives better side peak suppression and gives less noise accumulation. Thus, the extinction ratio of the modulators will impose a power penalty on the system.

III. Power Penalty Analysis

In our analysis, we assume a 16-Gbit/s multiplexed optical pulse stream @1.55\( \mu m \) is passed through a 4-stage cascaded MQW-EA modulators to demultiplex a 1-Gbit/s pulse stream. The control voltages in the consecutive stages are 4GHz, 2 GHz, 1 GHz and 500MHz respectively. The pulse shape is chosen to be hyperbolic-secant and the pulse width is 20 ps (FWHM). An erbium-doped fiber amplifier (EDFA) with a 1 nm optical bandpass filter and 30dB gain is placed in front of the demultiplexer to compensate the insertion loss. The frequency characteristics of the receiver is assumed to be a 1 GHz low-pass filter. The bit-error-rate (BER) performance is obtained in the worst-case manner that all channels other than the demultiplexed bit is '1'. In this case, the adjacent channel interference to the demultiplexed bit slot is the maximum.

Denote \( (I_1, \sigma_1^2) \) and \( (I_0, \sigma_0^2) \) as the signal levels and noise levels when a '1' and '0' are detected in a specific channel respectively. The noises considered include signal shot noise, thermal noise, amplified spontaneous emission noise, signal- spontaneous emission noise and spontaneous-s spontaneous emission noise. All signals or noises subjected to the frequency response of the receiver are obtained by following the analyses as in [6,7]. The BER is then a function of the parameter \( Q \) where \( Q = (I_1 - I_0)/(\sigma_1 + \sigma_0) \). The degradation in the modulators’ extinction ratios will degrade the extinction ratio of the resultant demultiplexing waveform and thus the crosstalk and noise from the other channels within the sampling time will impose a power penalty to the receiver. The power penalties of different extinction ratios of the resultant demultiplexing waveforms and different absorption parameters \( q' \) are shown in Figure 5. It is shown that the optimal value of \( q' \) is 4 and the extinction ratio of cascaded modulators should be at least 18dB for less than 0.5dB power penalty.

IV. Conclusion

In summary, we have studied the performance of the ultrafast time-division demultiplexers using cascaded MQW-EA modulators or switches. The power penalties due to the modulator’s extinction ratio and the modulator’s absorption characteristics are studied. This kind of ultrafast time-division demultiplexer can increase the demultiplexing rate or reduce the bandwidth requirement of the related electronics. Also, its feasibility to be monolithically integrated is very attractive in terms of practicality and cost-effectiveness.
REFERENCES


Fig. 2. Modulation waveform of cascaded MQW modulators with sinusoidal control voltages in a single stage.

Fig. 1. (a) System configuration of cascaded modulators as a time-division demultiplexer. (b) Schematic of stage i of the cascaded modulator configuration. CM: a single stage of cascaded modulators, PS: Phase-shifter, MQW-MOD: MQW modulator/switch.

Fig. 3. Modulation characteristics of cascaded MQW modulators with different absorption characteristics.
Fig. 4. Demultiplexing profile of a four-stage cascaded MQW modulators

Fig. 5. Power penalty due to extinction ratio in cascaded MQW modulators configuration