Optimized Performance Map of an EAM for Pulse Generation and Demultiplexing via FROG Characterisation

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Abstract: We demonstrate the complete characterization of a sinusoidally driven electro-absorption modulator (EAM) over a range of RF drive voltages and reverse bias conditions. An accurate performance map for the EAM, to be employed as a pulse generator and demultiplexer in an optical time division multiplexed (OTDM) system, can be realized by employing the Frequency Resolved Optical Gating technique. The generated pulses were characterized for chirp, extinction ratio (ER) and pulse width (< 4 ps). The optimization of the EAM's drive conditions is important to ensure that the generated pulses have the required spectral and temporal characteristics to be used in high-speed systems. The ER and pulse width also influence the demultiplexing performance of an EAM in an OTDM system. This is confirmed by utilizing the EAM as a demultiplexer in an 80 Gb/s OTDM system and measuring the BER as a function of the received optical power for various values of the ER and pulse width. Simulations carried out verified the experimental results achieved.

Keywords: Pulse generation, demultiplexing, electro-absorption modulator (EAM), FROG

1. Introduction

The expected consumer demand for voice over IP (VoIP), high-speed internet, standard definition TV (SDTV) and particularly high definition TV (HDTV) services, has coincidingly increased the demand for higher bandwidth capabilities [1]. Optical time division multiplexing (OTDM) and hybrid wavelength division multiplexing (WDM)/OTDM are technologies that could be used for greatly increasing the capacity of optical communication systems without increasing the cost (by avoiding high-speed electronics). As optical systems move towards higher data rates and also migrate from non-return to zero (NRZ) to return to zero (RZ) format (due to enhanced performance of RZ systems at 40 Gbit/s and beyond) [2], the impact of chromatic dispersion in transmission fiber becomes more dramatic and the use of dispersion management techniques and/or optical fiber nonlinearities to counteract the dispersive effects, must be precisely regulated [3]. In addition to knowing the dispersion parameter of the transmission fiber, it is essential to know the chirp, pulse width and ER of the optical data signals generated at the transmitter of these high-speed systems. This is necessary since the chirp of the optical pulses determines the propagation of the optical data [4]; the pulse width limits the bandwidth capacity of the system and also contributes to inter-symbol interference [5]; and the ER limits the systems performance as a consequence of coherent interference noise between individual OTDM channels [6]. Hence, to optimize the overall performance of a high-speed photonic communication system, it is vital to characterize accurately the intensity, picosecond duration and phase of the optical RZ data signals generated at the transmitter. As standard measurement techniques will not suffice in yielding such information, an alternative technique known as Frequency Resolved Optical Gating (FROG) is employed for the accurate and complete characterization of the signals.

Short optical pulses can be generated by employing several different techniques such as mode locking, gain switching or by gating Continuous Wave (CW) light with an Electro-Absorption Modulator (EAM). Mode locking of semiconductor or fiber lasers is a common technique used to generate short optical pulses operating at high frequencies. However, the cavity complexity and limited tunability of the mode locking repetition rate act as major disadvantages associated with this technique. Alternatively gain-switching offers smaller footprint, efficient wavelength-stable performance and the ability to produce high-repetition rate pulses. Nevertheless this technique has a number of shortcomings such as the generated pulses exhibiting a large chirp, timing jitter and a degraded Side Mode Suppression Ratio (SMSR) [7]. A suitable technique to generate picosecond optical pulses that exhibit high spectral and temporal purity involves gating a CW light source with a sinusoidally driven EAM [8]. This technique has been demonstrated to be reliable and is a stable source of short optical pulses. Low drive voltage, high modulation efficiency and polarization insensitivity are other qualities that make the semiconductor based EAM very attractive for high-speed optical communication systems.

When considering OTDM systems it is equally important to have stable demultiplexing schemes in addition to having a suitable pulse source [9]. The use of EAMs for optical demultiplexing has been demonstrated at rates up to 160 Gb/s [10]. One such scheme would require that the switching window of the EAM when used for demultiplexing should have a narrow width (approximately 30% of bit slot to avoid interference), high extinction ratio, small timing jitter and long term stability in order to ensure error free performance at the receiver [11,12].

In this work, we demonstrate a map which shows an optimised region (chirp, ER and width) of operation when the bias and RF drive voltages of an EAM are varied. Hence, by

completely characterizing the pulses over a range of driving conditions, a performance map can be constructed which illustrates the optimum operating condition of the EAM not only as a pulse generator but also as a demultiplexer. The technique of frequency resolved optical gating is used to realize the accurate and complete characterization.

2. Pulse Generation and Characterization

The experimental setup we used for the DC transfer characterization and the subsequent pulse generation is illustrated in Figure 1. The EAM was a commercially available fibre pigtailed InP modulator that operates over the entire C-band. The basic setup for static characterisation consists of an external cavity laser (ECL) providing an output power of 6 dBm to the EAM through a polarisation controller. A power meter measures the transmission loss as a function of reverse bias, thus illustrating the components variation in throughput with respect to a change in reverse bias voltage for a variety of wavelengths, and as a result this will have an impact on the optimum operating condition of the EAM for pulse generation and demultiplexing applications.
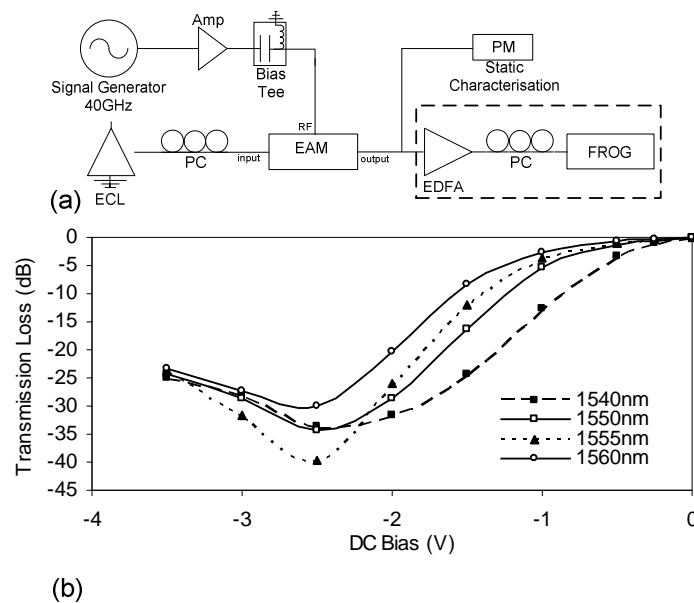

(a)

(b)

Fig. 1   (a) Experimental setup used for pulse generation and (b) DC transfer characteristic measured at a range of wavelengths.

The 40 GHz optical pulses were generated by gating CW light from an ECL by applying a sinusoidal wave of varying peak to peak amplitude in conjunction with a DC bias via a bias tee to the modulator. The pulse characterization was performed by pre-amplifying the generated pulses using a short pulse erbium doped fiber amplifier (EDFA) followed by a polarization controller (PC), as indicated by the dotted box (Fig 1a). The PC ensured that an optimum polarization state is maintained before the pulses are measured by the FROG. The bias voltage was then altered between 1 and 2 V in steps of 0.2 V and the pulses were analyzed at RF drive voltages of 2.5, 2.8, 3.1, 3.4 and 3.7 Vpp respectively. The generated pulses were subsequently amplified to an average power of 10 mW and characterized using the standard Second Harmonic Generation (SHG) FROG technique as fully explained in [13]. Pulse retrieval for the characterization carried out in this work routinely gave low retrieval errors of less than 0.0004 with 64 x 64 grid (i.e., 64 spectral and temporal points). In addition to the FROG measurement, the generated pulses were measured using an optical spectrum analyzer and a 50 GHz oscilloscope in conjunction with a 50 GHz detector.

The bias voltage and RF drive applied to the EAM were initially set to those values thought to generate optimum pulses from the setup, as deduced from the transfer characteristic (Fig. 1b). Figure 2 (a) displays the generated 40 GHz pulses measured with a 50 GHz oscilloscope in conjunction with a 50 GHz detector. Due to the limited response time of this detection system, it is difficult to obtain information about the characteristics of the generated pulses. In addition, as the bias voltage and RF drive signal applied to the EAM were varied, no noticeable changes were observed on the oscilloscope (not even pulse width). The pulses were subsequently characterized using the FROG technique.
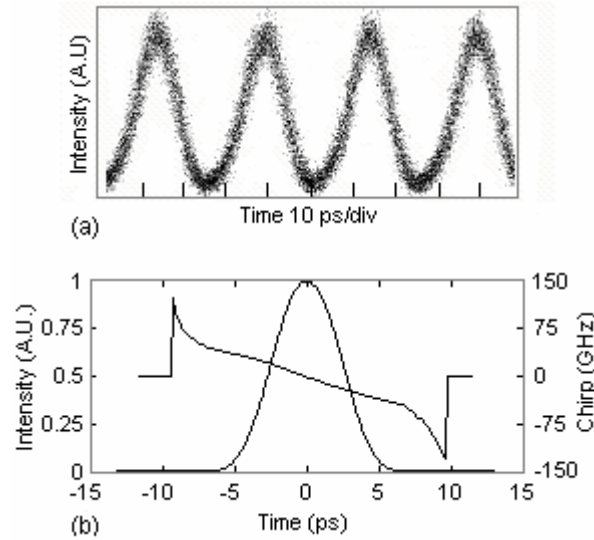
Fig. 2   Retrieved intensity and chirp of pulses generated using CW laser followed by external modulator. (a) Generated pulses characterized with 50GHz oscilloscope and (b) Generated pulse and corresponding chirp characterized using the FROG technique.

Figure 2 (b) illustrates an example of the intensity and phase as measured using the FROG technique. The FROG technique enabled characterization of the EAM's performance in terms of pulse width, frequency chirp and extinction ratio (ER). By monitoring each of these parameters at various bias and drive conditions, an accurate performance map for the EAM could be deduced. Figure 3 illustrates how the full width half maximum (FWHM) of the generated pulses, depends strongly on the reverse bias. As the reverse bias is increased, there is a noticeable decrease in pulse width. From these results, we can deduce that to achieve the narrowest width the EAM must be biased at 2 V with a large RF drive voltage. Similarly, the frequency chirp also depends strongly on the bias condition of the EAM. As the reverse bias increases there is a considerable decrease in frequency chirp (expressed in GHz/ps across the center of the pulse). The minimum chirp and thus near transform limited pulses (TBP = 0.43) can be achieved by biasing the EAM in the 1.6 to 2 V bias range.
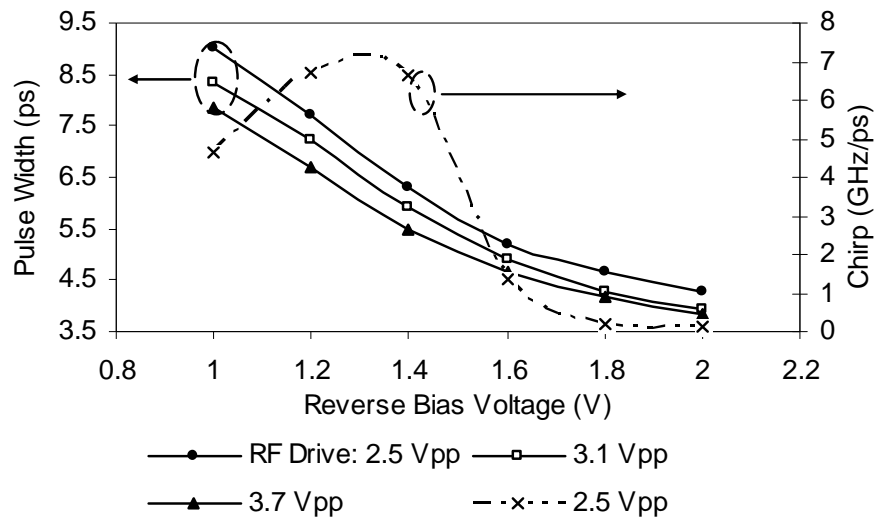
Fig. 3   Pulse width (FWHM) and frequency chirp as a function of reverse bias and RF drive voltage.

If there is a sufficient signal to noise ratio, the FROG can accurately measure the extinction ratio of the pulse or gate up to approximately 35 dB. The extinction ratio is an important pulse parameter, but it is also important to have good gate extinction when employing the EAM as a demultiplexer to ensure optimum BER performance. Therefore this parameter is dealt with in more detail in the next section which is concerned with optimizing the EAM for demultiplexing.

2. High Speed Demultiplexing

Figure 4 illustrates the 80 Gb/s test bed used in this work to characterize the demultiplexing performance of a sinusoidally driven EAM. The transmitter consisted of a commercially available Tunable Mode Locked Laser (TMLL) which was optically amplified and filtered before it was modulated with a Pseudo Random Bit Sequence (PRBS) of length 2^7-1 with the aid of a Mach-Zehnder modulator. The PRBS was generated by a 10 Gb/s Pulse Pattern Generator (PPG). The resultant STM-64 RZ optical signal was multiplexed up to 80 Gb/s by passing it through a passive fiber interleaver. The polarization state of each tributary was

maintained by placing a polarization controller at the input and a polarizer at the output of the multiplexer.
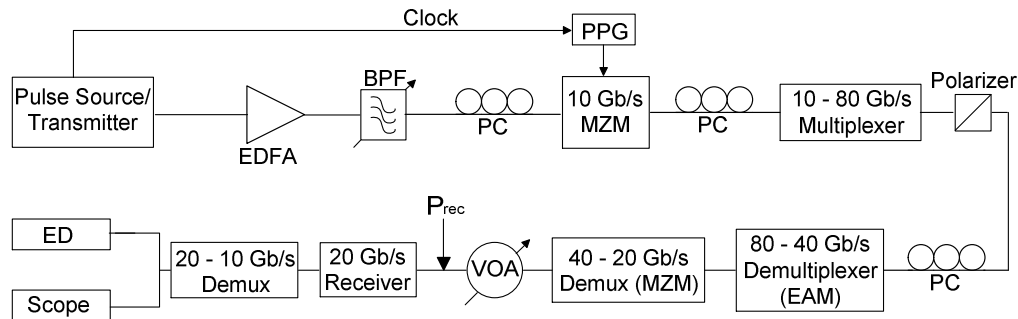

Fig. 4   80 Gb/s test bed used to accurately measure the BER performance of an EAM operating as a 80-40 Gb/s demultiplexer.

The 80 Gb/s system was initially demultiplexed down to 40 Gb/s using the electro-absorption modulator. The bias an RF drive voltages applied to the EAM are consistent with the pulse generation experiment described in section 1. This produced a varying gate width and ER which would have an effect on the optimum system demultiplexing performance. As before the system was analyzed for a range of reverse bias conditions and RF drive voltages. The optical data was demultiplexed down to 20 Gb/s with the aid of a MZM before it was optically pre-amplified and received. Demultiplexing down to the base rate (10 Gb/s) was carried out with the aid of an electrical demultiplexer. BER rate measurements were performed for a range of received optical powers (measured before the 20 Gb/s receiver stage). Signal analysis was carried out with a 50 GHz oscilloscope in conjunction with a 50 GHz detector and the BER performance was monitored with an error detector.

The bias and RF driving conditions of the EAM were altered and a BER test was carried out for each permutation. Over the range of EAM operating conditions the gating window is always narrow enough to correctly demultiplex from 80 to 40 Gb/s without introducing errors. It is therefore the ER of this gate combined with the varying signal to noise ratio (SNR) that is the primary cause of induced errors and hence large power penalties on the system. The magnitude

of the ER changes due to the transmission profile of the EAM (Fig 1b). Figure 5 illustrates the ER ratio of the generated pulses (measured using FROG) when a drive voltage of 3.7 Vpp is applied the EAM at each bias point from 1 to 2V, and it is seen to be at its peak at a bias voltage of 1.4 V. Beyond this bias point the ER drops off rapidly and this degradation in ER with respect to the bias voltage may cause corresponding power penalties during the demultiplexing process.
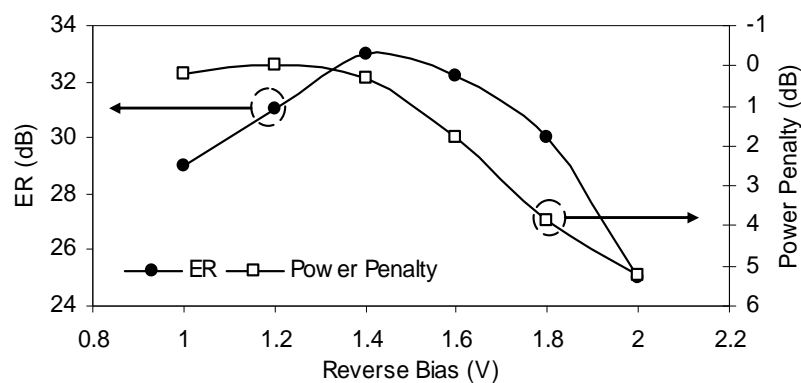

Fig. 5   Experimentally measured extinction ratio and BER performance at $1e^{-9}$ as a function of reverse bias.

BER tests were performed at various EAM operating conditions and the result is plotted in terms of the power penalty at a bit error rate of $1e^{-9}$ relative to the optimum performance (measured at point P_{rec} as seen in Fig. 4) and the reverse bias condition of the EAM.

At a reverse bias of 1 V the extinction ratio is assumed large enough to produce error free performance. As the bias increases the ER also increases but this improvement is somewhat negated by a decrease in SNR as deduced from the transfer characteristic in Fig. 1(b). Even though the optimum ER is realized at a bias point of 1.4 V there is a degraded SNR at this level than that at 1 or 1.2 V, due to a steeper gradient on the transmission curve. This results in a small power penalty with respect to 1.2V. After this point the ER decreases and combined with a decreasing SNR a larger power penalty of up to 5.5 dB at a bias point of 2 V is experienced. The optimum BER performance is thus achieved while biased at 1.2 V.

3. Simulation Model

To verify these experimental results, the 80 Gb/s OTDM system was modeled using the Virtual Photonics Incorporated (VPI) software package. Figure 6 shows a schematic of the setup. The model initially creates a secant optical pulse with a FWHM of 2.1 ps at a repetition rate of 10 GHz to mimic that of the TMML in the experimental apparatus. The output of the pulse source is split into eight optical channels which are then individually modulated with a 10 Gb/s signal via eight amplitude modulators. Each tributary is time delayed before being optically multiplexed to form an 80 Gb/s OTDM data signal. The Virtual Photonics Incorporated software package provides a measured electro-absorption modulator (EA_measured) which allows the input of the DC transfer characteristic as experimentally measured in section 1.
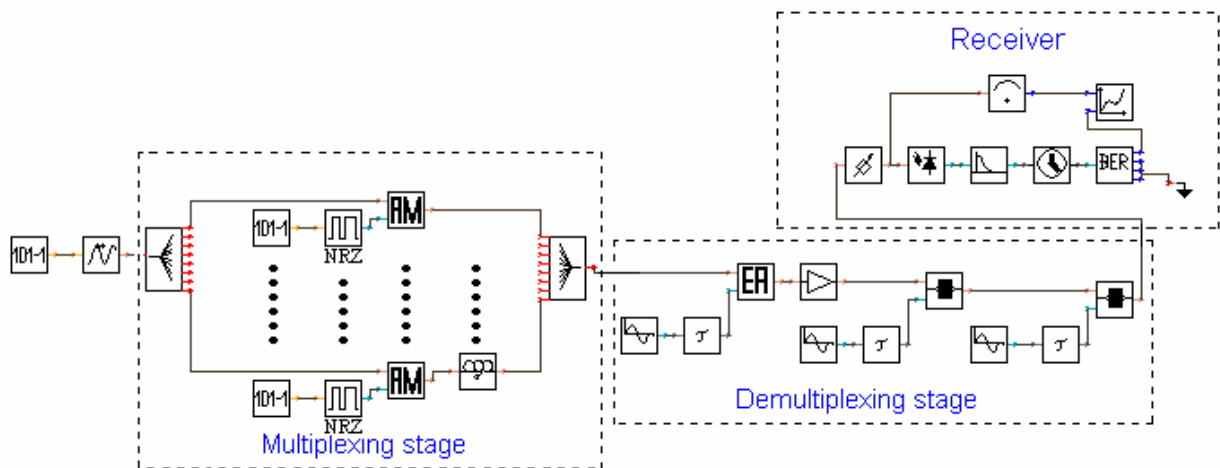

Fig. 6   Simulation model of 80 Gb/s OTDM system using VPI software package

The EAM is again used as an 80 to 40 Gb/s demultiplexing component. The 40 Gb/s data signal is optically amplified and then demulitplexed down to the base rate of 10 Gb/s using two Mach-Zehnder modulators (optimized to mimic the performance of MZM and electrical demultiplexer in experiment). The receiver consists of a variable optical attenuator, photodetector, low pass filter and a clock recovery component.

As in the experimental procedure, the reverse bias is altered between 1 and 2V in steps of 0.2V.

The RF drive voltages were also altered correspondingly. BER tests were performed at the various EAM operating conditions and the result is plotted in terms of the power penalty at a bit error rate of 1e^{-9} (measured at after the VOA) and the reverse bias condition of the EAM. Figure 7 illustrates the ER and BER performance as a function of reverse bias.
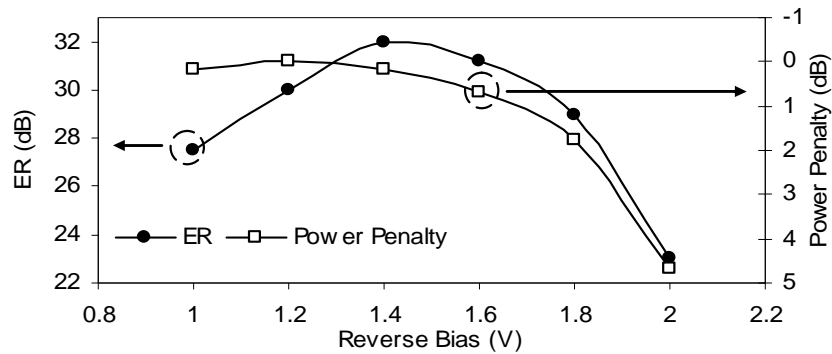

Fig. 7   Extinction ratio and BER performance at 1e^{-9} as a function of reverse bias, measured from a VPI model.

An excellent correlation is observed between the simulation and experimental results. The extinction ratio (ER) measured using the FROG technique shows good agreement with the simulation results. Again, as with the experiment, an optimum ER is realized at a reverse bias of 1.4 V and then falls off rapidly. This ER fall off is again due to the steepness of the transmission profile of the EAM and shows discrepancies of less than 1 dB in comparison to the experiment, which is in excellent agreement. The BER performance at a series of bias conditions shows the same trend as that experienced in the experiment. There is a slightly smaller power penalty of 4.8 dB experienced in the simulation model. The power penalty does not fall off as rapidly in the modeled system due to a more ideal receiver than that used in the experiment which suffers from a lower noise level, thus reducing the power penalty measured at 1e^{-9}. As in the experiment the optimum BER performance is realized at a reverse bias of 1.2 V.

4. Conclusion

We have demonstrated the complete characterization of an electro-absorption modulator over a wide range of RF drive voltages and reverse bias conditions for pulse generation and optical demultiplexing applications. The Frequency Resolved Optical Gating (FROG) technique was employed to create a complete performance map for the EAM in terms of pulse width (PW), frequency chirp and extinction ratio (ER). The EAM generated pulses with a varying FWHM between 9 and 4 ps, and with an extinction ratio varying from 22 and 33 dB. The frequency chirp (measured in GHz/ps) also varied with respect to the EAM's reverse bias from about 7 to 0 GHz/ps. By compiling this performance map we are able to tailor the generated pulses for use in high-speed optical systems.

The EAM is also utilized as a demultiplexing component in an 80 Gb/s OTDM system and it's performance was monitored over a range of bias conditions. A power penalty of 5.5 dB was experienced at a reverse bias of 2 V. This penalty was the result of the gates varying ER and a changing signal to noise ratio (SNR) due to the gradient of the EAM's transfer characteristic. Finally the experimental results were verified using a simulation model which exhibited excellent correlation. This result demonstrates how the FROG may be used for optimizing both transmitters and receivers (demultiplexers) for high speed OTDM systems.

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