

Efficient performance optimization of SOA-MZI devices

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Abstract: We present a novel characterization method for semiconductor optical amplifier Mach-Zehnder interferometer (SOA-MZI) switches which combines a pump-probe measurement with an interferometer bias scan. In addition to a wealth of information on the switching dynamics for all operating points of the switch, we can create an extinction map to pinpoint regions of highest extinction for optimizing all-optical ultrafast switching. We experimentally verify the accuracy of this characterization method by performing a wavelength characterization at the optimal bias point and a nearby, non-optimal point. A 1-dB penalty was observed.

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1. Introduction

Ultrafast all-optical signal processing can potentially offer increased network capacity, reduced complexity, and reduced latency for telecommunication networks. Practical implementation of

such capabilities requires integrated all-optical devices for ease of manufacturing, installation, and operation. The semiconductor optical amplifier Mach-Zehnder interferometer (SOA-MZI) is an integrated all-optical logic gate which can fulfill these requirements. Demonstrations using this device have included demultiplexing at speeds up to 336 Gb/s [1], [2], bit-wise switching at 80 Gbit/s [3], and optical regeneration [4, 5].

Conceptually, device operation is straightforward, relying on optically inducing a differential phase shift between the SOAs located in each of the two interferometer arms. However, in practice, determining the optimal operating point for high extinction and ultrafast switching can be time-consuming since optimization must be performed over a large parameter space which includes the signal and control pulse energies, their relative delay, and the bias currents for the switching and amplifying SOAs.

To address this issue, we have developed a novel characterization technique to quickly identify the optimal operating point of SOA-MZI switches. We measure a bias map of the constructive and destructive interference fringes of the interferometer for each value of the signal-control delay. By observing how the interference fringes change with signal-control delay, we obtain insight into the device dynamics at different bias points for the SOA-MZI. From this information, we also create an extinction map which locates regions of high extinction for optimal ultrafast switching. This technique greatly simplifies the operation of single SOA-MZI gates, and will be even more critical for operation of multi-gate SOA-MZI devices in future optical signal processing applications.

2. Optimization method

We used a semiconductor optical amplifier Mach-Zehnder interferometer (SOA-MZI) provided by Alphion Corporation (Fig. 1). In single-ended operation, two switching SOAs (shown in orange) and 3 amplifying SOAs (shown in yellow) are used. The device operates as follows: signal pulses (shown in blue) are split into identical copies traveling in each arm of the interferometer. The static bias of the interferometer is determined by the bias currents of the switching and amplifying SOAs. In the absence of any control pulses, the static bias determines whether the signal pulse recombines at the output of the interferometer destructively or constructively. When a control pulse (shown in red) is coupled into one arm of the interferometer, it induces a change in the gain and phase of the signal pulse in that arm through cross-phase and cross-gain modulation in that switching SOA. The signal pulse in the opposite arm sees no effect. This induced phase difference changes the interferometer bias from destructive to constructive interference (non-inverting operation) or vice versa (inverting operation).

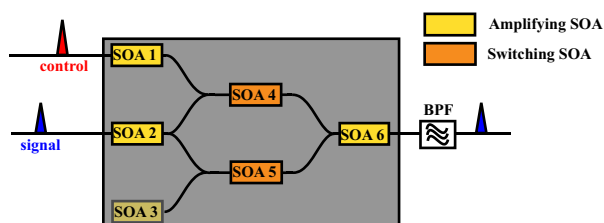


Fig. 1. Semiconductor optical amplifier Mach-Zehnder interferometer (SOA-MZI). SOAs 4,5 perform switching while SOAs 1-3, and 6 amplify. SOA 3 is not used in single-ended operation. BPF is a band-pass filter.

To determine the optimal operating point of this device, we must determine the correct bias current settings for the switching and amplifying SOAs, the optical power required to induce a π -phase shift, and the correct signal-control delay. To do this efficiently, we have developed the

pump-probe bias scan technique. Figure 2(a) shows the experimental setup of this measurement technique.

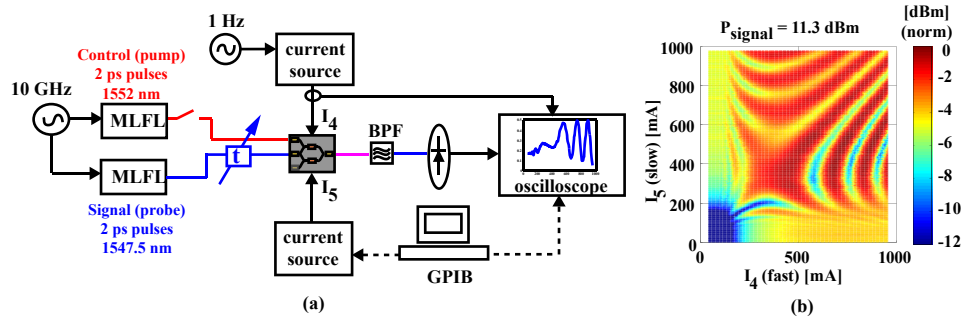


Fig. 2. (a) Experimental schematic for the pump-probe bias scan. Static pump-probe bias scans are made without the control pulse. Dynamic bias scans are made with the addition of the control pulse. BPF is band-pass filter. τ is the signal-control delay. (b) Static bias map of the SOA-MZI interferometer. Areas of constructive interference show up as deep red while areas of destructive interference show up as deep blue.

First, we map out the static bias of the interferometer. We measure the average output power of the signal pulses over all possible values of switching SOA bias currents. Control of the SOA current source through GPIB proved prohibitively slow, taking 9 hours for a single bias map. To improve the speed, we used a 1-Hz sawtooth wave to dither the current on SOA 4, reducing the entire scan to 7 minutes, or 185 points per second. The frequency of the dither was chosen to be as fast as possible while reducing unwanted thermal effects and remaining within the bandwidth of our current source. Figure 2(b) shows the resulting static bias map of the SOA-MZI. The interference fringes of the interferometer show up clearly in the plot, indicating multiple areas of destructive interference (nulls) and constructive interference (peaks).

Our main interest, however, is in how the optical control pulses induce switching in the SOA-MZI. To observe this, we measure a dynamic pump-probe bias map by coupling control pulses into the device and measure a static bias map at each value of the signal-control delay τ . Thus, we can observe the effect of the control pulse on the signal pulse at all possible current biases and signal-control delays. In effect, if we consider the control pulses to be our “pump” pulses and our signal pulses to be our “probe” pulses, we are simultaneously performing a pump-probe measurement [6] over all possible SOA current biases. By arranging our series of static bias scans in order of increasing signal-control delay, we can create a dynamic movie of the all-optical switching dynamics, as shown in Fig. 3(a). For this measurement, the control pulses are generated by a mode-locked fiber laser at 1552 nm with a repetition rate of 10 Gbit/s and are inserted into one arm of the interferometer. Signal pulses are generated with a second, synchronized mode-locked fiber laser at 1547.5 nm with a repetition rate of 10 Gbit/s. The average power of the control pulses is 0.4 dBm and the average power of the signal pulses is -8.1 dBm. Figure 3(b) shows the relative control-signal delay for each frame of the dynamic bias map and Fig. 3(c) shows the switching window at the operating point “X” on Fig. 3(a). The switching window is the plot of the output signal power at each control-signal delay. We see that the presence of the control pulse shifts the bias of the interferometer and moves the signal pulse at point “X” from destructive to constructive interference. This results in non-inverting operation. We can also observe the slow carrier recovery time of the switch, limiting single-ended switching performance in the SOA-MZI to about 20 Gb/s.

In addition to information about switching dynamics, we can use this data to accurately pin-

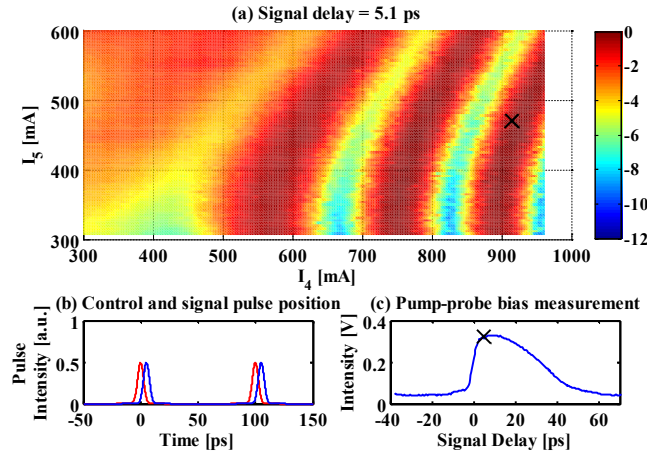


Fig. 3. (a) Dynamic bias map of the SOA-MZI interferometer. (b) Relative signal and control pulse positions corresponding to each frame of the bias map. (c) Switching window plot at position "X". (Size: 446 KB.)

point the optimal operating point for high-extinction ultrafast switching. We create an extinction map by calculating the extinction at each operating point by subtracting the minimum power output from the maximum power output. Figure 4(a) shows the extinction map of this measurement. Regions of high extinction occur for both non-inverting and inverting operation of the switch, and are separated by regions of low extinction. We find the optimal extinction for non-inverting operation to be 8.8 dB at $I_4=893.5\text{mA}$ and $I_5=470.0\text{mA}$, marked by the black square. To verify the accuracy of this measurement, we perform a 10-Gbit/s wavelength conversion at this operating point and compare it to a wavelength conversion performed at a nearby, non-optimal operating point. We arbitrarily choose the nearby operating point to be $I_4=905.5\text{mA}$ and $I_5=476.6\text{mA}$, marked by the black triangle. Figure 4(b) compares the BER at both operating points. The non-optimal operating point results in an additional 1-dB penalty as compared to the optimal point found using this optimization method.

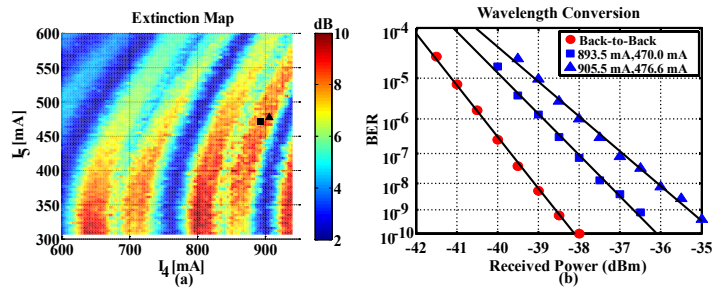


Fig. 4. (a) Extinction map. Regions of high extinction (red) are separated by regions of low extinction (blue). (b) Bit-error rate plot of wavelength conversion performed at the optimal operating point for non-inverting switch operation (square) as compared with wavelength conversion performed at a nearby non-optimal point (triangle).

3. Conclusion

Semiconductor optical amplifier Mach-Zehnder interferometers (SOA-MZI) offer ultrafast all-optical switching capabilities in a compact integrated package. Practical operation of the SOA-MZI logic gate is complicated by the time-consuming process of locating the optimal bias point for high-extinction ultrafast switching. This issue is further compounded for future multi-gate SOA-MZI optical signal processing. Our pump-probe bias scan technique allows us to quickly and effectively discover the optimal operating point for the SOA-MZI logic gate. In this paper, we have focused on single-ended operation of the SOA-MZI logic gate, but this same technique is easily adapted for differential operation by the addition of a second control pulse offset by a constant value from the first control pulse. The accuracy of this technique is indicated by the 1-dB penalty between the optimized and non-optimized operating points for 10-Gbit/s wavelength conversion.

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