Comparison of three nonlinear interferometric optical switch geometries

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Abstract

We present an experimental study of ultrafast all-optical interferometric switching devices based upon a resonant nonlinearity in a semiconductor optical amplifier (SOA). We experimentally compare three configurations: one based upon a Sagnac interferometer and the other two based upon Mach–Zehnder interferometers. By using picosecond pulses, we characterize the switching window of the three devices in terms of both temporal width and output peak-to-peak amplitude. These results are found to be in close agreement with a previously developed theoretical model. Since these nonlinear interferometric switches use an active device as the nonlinear element, relatively low control pulse energy is needed to perform switching as compared to other techniques. As a result, these optical switches are practical for all-optical demultiplexing and ultrafast optical sampling for future lightwave communication systems. © 2000 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

Increasing the bandwidth capacity of lightwave networks has recently received considerable attention from the research community to address the growing traffic demands on today’s communication systems. All-optical switches and demultiplexers are an important development that enables high aggregate data rates to be achieved in optical time division multiplexed (OTDM) networks. Semiconductor optical nonlinearities with long recovery times (≥ 100 ps) have been used to demonstrate interferometric all-optical switches that promise to deliver switching and demultiplexing at terabit/s rates. These nonlinearities are typically based upon a resonant excitation in active or passive semiconductor nonlinear waveguides or optical amplifiers. Extensive experimental [1–5] and theoretical [6–9] analysis has been performed on various interferometric configurations of these devices. Due to the compact nature of these devices, many have been integrated indicating their practicality for future communication systems [10,11]. Optical switches which use an active semiconductor optical amplifier (SOA) as the nonlinear switching element have performed efficient switching demonstrations [12] using low control pulse energy (250 fJ) as compared to passive devices. As a
consequence, this paper focuses on the SOA-based interferometric switches.

We present an experimental follow-up study to a previously developed theoretical model [6] for three different interferometric geometries that use a semiconductor resonant nonlinearity to achieve optical switching. The performance of each device is evaluated and compared based upon the temporal response of the optical switch. By varying the switching window temporal size, both the relative output amplitude and minimum achievable window duration can be investigated for each geometry. We find that the experimental results of this study are in close agreement with the predicted values from the theoretical model. Finally, we conclude with a summary of the performance advantages of the three optical switches.

2. Optical switch geometries

Fig. 1 shows the three interferometric optical switches that we investigate both experimentally and theoretically. The first geometry, shown in Fig. 1, upper panel, is a Sagnac interferometer with an SOA offset from the center position of the fiber loop and is known as a terahertz optical asymmetric demultiplexer (TOAD) [1]. In the absence of a control signal, data pulses enter the fiber loop, pass through the SOA at different times as they counterpropagate around the loop, and recombine interferometrically at the 50/50 coupler at the base of the loop. Since both pulses see the same medium as they propagate around the loop, the data is reflected back toward the source. In the presence of the control signal, switching can occur. The control signal energy is chosen to be at least ten times the data pulse energy. When the control signal is injected into the loop, it saturates the SOA and changes its index of refraction. As a result, a differential phase shift can be achieved between the two counterpropagating data pulses to switch the data pulses to the output port. A polarization or wavelength filter is used at the output to reject the control signal and pass the switched data signal. Since the SOA is slowly recovering, data pulses that enter the switch immediately after the control pulse both see the SOA in approximately the same recovery state and do not experience a significant differential phase shift. The temporal duration of the switching window is determined by the offset of the SOA, $\Delta x$, from the center position of the loop. As this offset is reduced, the switching window size decreases. The size of the nominal switching window duration, $\tau_{\text{win}}$, is related to the offset position by $\tau_{\text{win}} = 2\Delta x / c_{\text{fiber}}$ (where $c_{\text{fiber}}$ is the speed of light in fiber).

The other two switch geometries shown in Fig. 1, middle panel, and Fig. 1, lower panel, are both based upon a Mach–Zehnder interferometer. In the absence of the control signals, the Mach–Zehnder is balanced in such a way as to send all data signals entering the device to the reject port (not shown on the figure). When control pulses are injected into the interferometer, a differential phase shift is briefly introduced between the two arms of the interferometer causing a data pulse to be switched to the output port. Similar to the TOAD, subsequent data pulses that pass through the switch see the slow recovery of both SOAs and are rejected. The slight difference between the two Mach–Zehnder geometries shown is with respect to the propagation direction of control and data signals. In the colliding pulse Mach–Zehnder (CPMZ) shown in Fig. 1, middle panel, the data and control signals counter-propagate through the interferometer. As a result, a filter is not needed at the output port to reject the control signals. However, the symmetric Mach–Zehnder (SMZ) in Fig. 1, lower panel, requires a filter at the output port to reject the control signals from the switched data signal since data and control signals co-propagate through the interferometer. Assuming the SOAs are positioned in the same relative location within the interferometer, the nominal switching window for both Mach–Zehnder configurations is determined by the temporal control pulse separation, $\Delta t_{\text{control}}$, of the signals Control 1 and Control 2 prior to entering the interferometer such that $\tau_{\text{win}} = \Delta t_{\text{control}}$.

Although the nominal switching window size provides an estimate of the switching window temporal duration, it does not account for the finite length of the SOAs within the interferometer. While the SOA length has little effect on the SMZ geometry, the minimum achievable switching windows for both the TOAD and CPMZ are constrained by the length of the SOAs [6]. By incrementally reducing the switch-
Fig. 1. All-optical SOA-based interferometric switch geometries: upper panel: terahertz optical asymmetric demultiplexer (TOAD), middle panel: colliding-pulse Mach–Zehnder (CPMZ), and lower panel: symmetric Mach–Zehnder (SMZ).

In this section, we develop a theoretical model to describe the operation of the three optical switch geometries. This model, which is based on previous work [6], is used in Section 4 to analyze the impact of the effective switching offset on the optical switching window performance. Note that although this model is not a rigorous device-level model, it does provide relatively good agreement between the predicted optical switch performance and experimental data. Since the switch geometries discussed in this paper are all based upon optical interferometry,
the output signal of the switch can be described by the following basic interferometric equation:

\[
P_{\text{out}}(t) = \frac{P_{\text{in}}(t)}{4} \left( G_1(t) + G_2(t) - 2G_1(t)G_2(t) \cos(\phi_1(t) - \phi_2(t)) \right).
\]

(1)

The input data signal is represented by \(P_{\text{in}}(t)\), and it is assumed that the interferometer is balanced so that there is initially no signal at the output. In the presence of one or more control signals, the two data signals (signals 1 and 2) that interfere within the interferometer experience a time-dependent gain, \(G_{1,2}(t)\), and phase shift, \(\phi_{1,2}(t)\), as they traverse the SOA. By introducing some form of asymmetry within the interferometer, either by appropriate timing of the control pulse(s) or by careful positioning of the nonlinear element(s), the two signals can experience different responses. This differential response results in the input data signal being switched to the output of the device.

For the simple model adopted here, the gain and phase shift experienced by signals travelling through the SOA is assumed to be described by the following temporal responses:

\[
G_{1,2}(t) = G_0 - \Delta G \int_{-\infty}^{\infty} h_{1,2}(t') P_{\text{clk}}(t' - t) dt'.
\]

(2)

\[
\phi_{1,2}(t) = \Delta \phi \int_{-\infty}^{\infty} h_{1,2}(t') P_{\text{clk}}(t' - t) dt'.
\]

(3)

The variable \(P_{\text{clk}}(t)\) represents the control signal whereas \(h(t)\) represents the impulse response of the SOA. Also, \(G_0\) is the initial gain of the SOA and \(\Delta G\) and \(\Delta \phi\) represent the amount of change in gain or phase when the control pulse traverses the SOA. Depending upon the direction of propagation of the data signal with respect to the control pulse, different impulse response functions must be used in Eqs. (2) and (3). For the case when the data and control signals co-propagate, the following single time-constant impulse response is assumed:

\[
h_{\text{co}}(t) = \Phi(t) \exp \left( -\frac{t}{\tau_{\text{SOA}}} \right).
\]

(4)

The step function, \(\Phi(t)\), accounts for the situation when the data signal is either leading or trailing the control pulse and \(\tau_{\text{SOA}}\) is assumed to be the dominant SOA recovery time constant. In contrast, the length of the SOA must be taken into account for the case when the data and control signals counter-propagate with respect to each other. The impulse response for the counter-propagating geometry is given as:

\[
h_{\text{ctr}}(t) = \exp \left( -\frac{t}{\tau_{\text{SOA}}} \right) \int_{-1/2}^{1/2} \Phi \left( x + \frac{c_{\text{SOA}} t}{2} \right) \times \exp \left( -\frac{2 x}{c_{\text{SOA}} \tau_{\text{SOA}}} \right) dx.
\]

(5)

In this equation, the step function accounts for the intersection of the counter-propagating data and control signals. Finally, \(c_{\text{SOA}}\) is the speed of the light through the SOA and \(l\) is its length.

Using Eqs. (1)–(5), the switching windows of the three optical switch geometries can be computed using the following approach. Based upon the switch geometry, the appropriate impulse responses, \(h_{1,2}(t)\), are computed for each of the data signals within the interferometer. For the SMZ configuration, \(h_{\text{co}}(t)\) is used for both impulse responses; for the TOAD, \(h_{\text{co}}(t)\) is used for one response and \(h_{\text{ctr}}(t)\) is used for the other; and finally, for the CPMZ, \(h_{\text{co}}(t)\) is used for both responses. The selected impulse responses are delayed by one another by the effective switching offset. Control pulses are convolved with each response and the result is used to compute the differential gain and phase evolution described by Eqs. (2) and (3). The output of the interferometer switch is then calculated using Eq. (1). Finally, in order to take into account the finite temporal width of the data signal, the data pulse is correlated with the output response of the interferometer. The resulting signal is normalized to the maximum output in order to simplify the comparisons between the different geometries as well as the experimental data. As in previous work, the constants used in computing the switching window performance are as follows: \(G_0 = 10\), \(\Delta G = 5\), \(\Delta \phi = 0.5\pi\), \(\tau_{\text{SOA}} = 400\) ps, \(l = 500\) μm, and finally \(n_{\text{SOA}} = 3.3\). Pulses with Gaussian temporal envelopes having a width of 1.6 ps are assumed for both the data and control signals. A comparison of the switching window performance for the three switch geometries using both the theo-
Optical switch characterization

To experimentally evaluate the performance of the three nonlinear interferometric optical switches, fiber-based versions of each configuration were constructed from discrete components. The nonlinear element used in each switch geometry is an Alcatel 1901 SOA biased at approximately 100 mA. Polarization controllers are used internally within each switch in order to align the interferometer for the proper condition for interference.

Each configuration was characterized using the test setup shown in Fig. 2. A 1.55 μm mode-locked fiber laser (MLL) is used to generate a continuous stream of 1.6 ps optical pulses at a 2.5 GHz rate. The pulse stream is amplified by an erbium-doped fiber amplifier (EDFA) and optically split into control signals and data signals for injection into the optical switch device-under-test (DUT). For the SMZ and CPMZ switch geometries (which require two control pulses) an optical delay line (ODL) is used to set the relative offset between the pulses to control the desired switching window size. In the TOAD geometry, an optical delay line inside the interferometer is used to change the SOA offset and set the switching window. For the SMZ and TOAD configurations, it is necessary to set orthogonal polarization states for the input control and data pulses using polarization controllers (PC). This enables the separation of the switched data signal from the control pulses at the output of the switch using a polarization filter.

For each switch under evaluation, the data and control pulse energies (average powers) are fixed at 4 fJ (10 μW) and 50 fJ (125 μW), respectively, when measured at the input facet of the SOAs inside the interferometer. A mechanical vibrator is used to quickly scan the data pulses in time over a 40 ps range to map out the switching window of the device under test. This technique provides a means of rapidly characterizing the switching window. While the TOAD is based upon the inherently stable Sagnac interferometer, thermal variations in the optical fiber cause the output of the fiber-based Mach–Zehnder switches to fluctuate slowly in time. By performing the scan at a rate faster than the thermal variations, switching windows of the fiber-based Mach–Zehnder switches can be obtained without resorting to complex stabilization techniques. (Note that thermal variations do not significantly affect the stability of any of these interferometers if integrated devices with short optical path lengths are used.)

The results of the TOAD optical switch characterization are described first. Using the test setup, experimental scans of the TOAD switching window were taken for various offsets and the results are summarized in Fig. 3, upper panel. The SOA position within the loop is varied so that the effective switching offset decreases from approximately 18 ps...
Fig. 3. Upper panel: experimental window scans of the TOAD optical switch, and lower panel: computed window scans using the model described in the text.

down to 0 ps in 1.6 ps steps. As the switching offset is initially decreased from a large offset, the window width decreases by the same proportion although the output amplitude remains relatively constant. At an offset of approximately 10 ps, however, the amplitude begins to decrease in direct proportion as well. This amplitude decrease is a result of the finite length of the SOA becoming a factor. At extremely small offsets, the switching window width does not decrease further since the finite data and control pulse widths become the dominant limitation. This trend continues until the effective switching offset is 0 ps at which point the switching window nearly vanishes. The results of the numerical simulation for the TOAD switching window, shown in Fig. 3, lower panel, are in good agreement with the experimental results. The long rising edge of the switching window is due to the finite length of the SOA whereas the sharp falling edge is only limited by the data and control pulse widths. Also, the window does not entirely disappear at zero effective switching offset as verified by the experimental data. Note, however, that the tops of the experimental windows for large offsets are not exactly flat as predicted in the simulations. This and other differences may be due to a variety of experimental nonidealities including variations in the source pulse energy and detector noise.

Under the same experimental conditions, similar measurements were taken for the SMZ and CPMZ switch geometries. The results of these scans are shown in Fig. 4, upper panel, and Fig. 5, upper panel. Due to its co-propagating nature, the SMZ has the unique characteristic of sharp edges on both the
rising and falling sides of the switching window. In contrast, since the CPMZ is a purely counter-propagating geometry, both edges rise and fall more slowly due to the finite SOA lengths. The simulated switching windows for the SMZ and CPMZ, shown in Fig. 4, lower panel, and Fig. 5, lower panel, also illustrate these characteristics. There are a few noticeable differences between the simulations and the experimental measurements. Although the tops of the experimental SMZ switching windows are relatively flat for large SOA offsets, the sense of the slope is opposite relative to the simulated values. The change in slope is a result of a 0.6 dB coupling variation throughout the translation length of the mechanical vibrator used to scan the data signal through the switching window. Additionally, there is a change in slope on the leading edge of the experimental windows that does not appear in the simulations. The source of this discrepancy is not fully understood at this time and is under investigation. In order to compare the results of the scans taken for the three optical switch geometries, the window peak-to-peak amplitude and FWHM were computed for each offset. The results of the amplitude measurements on the experimental and theoretical switching windows are summarized in Fig. 6, upper panel, and Fig. 6, lower panel, respectively. As shown in these figures, the CPMZ is the first switch to decrease in amplitude as the effective switching offset decreases. The finite SOA lengths in the counter-propagating geometry cause this reduction in the output amplitude. In contrast, the amplitude of the co-propagating SMZ switch...
Finally, the computed FWHM switching windows for the different geometries are shown in Fig. 7. Fig. 7, upper panel, shows the width of the experimental scans, whereas Fig. 7, lower panel, is computed using the theoretical model. The minimum detectable switching window sizes measured for the experimental configurations of the SMZ, TOAD, and CPMZ switches are 2.5 ps, 3.5 ps, and 8.3 ps, respectively. These minimum switching window widths agree closely with the minimum values predicted by the theoretical model. When the switching offset is reduced further beyond the values shown in Fig. 7, upper panel, the output amplitude is too small to accurately compute the window width. While the theoretical trend of the window sizes agrees well with the experimental data for the TOAD and SMZ, the experimental data for the CPMZ does not match the simulation as well for small switching offsets. A possible explanation for this difference is that there is greater experimental error in the measurement of the CPMZ window size since the output signal from the CPMZ (see Fig. 5, upper panel) is roughly half that of the TOAD and SMZ and, therefore, closer to the noise floor of the detector. The lower output signal of the CPMZ is due to additional splitting losses experienced by the switched output signal for a given data pulse energy. Furthermore, the simple theoretical model used in this study may not adequately account for other physical device level effects that may influence the switching behavior observed in the experimental trend.

5. Conclusion

In conclusion, we have characterized the switching response of three different geometries of ultrafast nonlinear interferometric optical switches. Although there are small deviations, our experimental results show good agreement with a simple impulse response numerical model. Further experimental investigations and refinements of the numerical model to include more detailed physical effects, such as ultrafast semiconductor optical nonlinearities, may account for the differences observed between theory and experiment. Of all the geometries considered, the SMZ switch exhibits the best performance in terms of the minimum switching window width and output peak-to-peak amplitude. The performance of the CPMZ switch, on the other hand, is somewhat limited by the counter-propagating geometry and finite SOA lengths. However, it has the advantage that it is not necessary to reject the control signal at
the output port. Finally, the TOAD has nearly comparable performance to the SMZ but is an inherently balanced interferometer unlike the two fiber-based Mach–Zehnder geometries used in this study. The control pulse energy requirements of all three devices studied are extremely low (< 50 fJ at the SOA facet) due to the active nature of the nonlinear elements used in the interferometers. This is at least an order of magnitude less than the energy required by passive structures. Although this study only considered fiber-based interferometric switches, these results apply equally to integrated devices based on similar geometries.

References