A novel fast optical switch based on two cascaded Terahertz Optical Asymmetric Demultiplexers (TOAD)

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Abstract: A novel optical switch based on cascading two terahertz optical asymmetric demultiplexers (TOAD) is presented. By utilizing the sharp edge of the asymmetric TOAD switching window profile, two TOAD switching windows are overlapped to produce a narrower aggregate switching window, not limited by the pulse propagation time in the SOA of the TOAD. Simulations of the cascaded TOAD switching window show relatively constant window amplitude for different window sizes. Experimental results on cascading two TOADs, each with a switching window of 8ps, but with the SOA on opposite sides of the fiber loop, show a minimum switching window of 2.7ps.

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1. Introduction:

Ultrafast optical demultiplexers are essential components of optical time division multiplexed (OTDM) networks operating at 100 Gb/s and faster. Present approaches to optical demultiplexing include using switches based on soliton gates [1], nonlinear loop mirrors [2], Terahertz Optical Asymmetric Demultiplexer (TOAD) [3], Semiconductor Laser Amplifier in a Loop Mirror (SLALOM) [4], Ultrafast nonlinear interferometer (UNI) [5], Mach-Zehnder interferometer with semiconductor optical amplifier [6,7], and Michelson interferometer with semiconductor optical amplifiers [8]. Due to the simplicity of design and low switching energy, the TOAD has been used in numerous OTDM systems and network demonstrations [9-14]. The TOAD consists of an optical loop mirror with an SOA placed off centered in the loop. The offset from the center determines the switching window width of the TOAD, as the asymmetry leads to a difference in arrival time between the two counter propagating data pulses at the SOA. A precisely timed clock pulse is injected into the loop such that its arrival at the SOA provides a relative π phase shift to the data pulse entering the SOA after the clock pulse has hit the SOA. This results in constructive interference at the output of the TOAD and the output pulse emerges.

One limitation of the TOAD approach is the finite propagation time of the pulse across the SOA [15]. If the offset of the SOA from the center is decreased such that the SOA starts to straddle the center of the loop, the effective SOA length that the two counter propagating pulses see is reduced. The decrease in effective SOA length leads to a reduction in the contrast ratio of the TOAD switching and thus, an excess power penalty. The effective length of the SOA required for producing the relative π phase shift places a practical limitation on the switching window size of the TOAD to be greater than the propagation time of the pulse through the SOA. The smallest switching window size obtained with a TOAD is 3.5ps [16].

In this paper, we demonstrate a new method of achieving narrow switching windows by cascading two TOADs, each with the SOA on opposite sides of the fiber loop. This method overcomes the limitation on the switching window placed by the length of the SOA.

2. Principle of operation

A characteristic of the TOAD switching window is that the rising and falling edges have different slopes [16]. The location of each edge is determined by the side of the fiber loop that the SOA is placed with respect to the control port. If the SOA is placed on the same side of the loop as the control port then the rising edge of the switching window is very steep, limited only by the clock pulse width. The falling edge slope of the switching window is a result of the clock and the counter propagating data pulses meeting inside the SOA and is thus related to the propagation time of the pulse through the SOA. If the SOA is placed on the opposite side of the loop, as the control port, the two edges are interchanged and the falling edge of the switching window is much steeper than the rising edge. Figure 1 shows the switching windows with the SOAs on different sides of the loop.

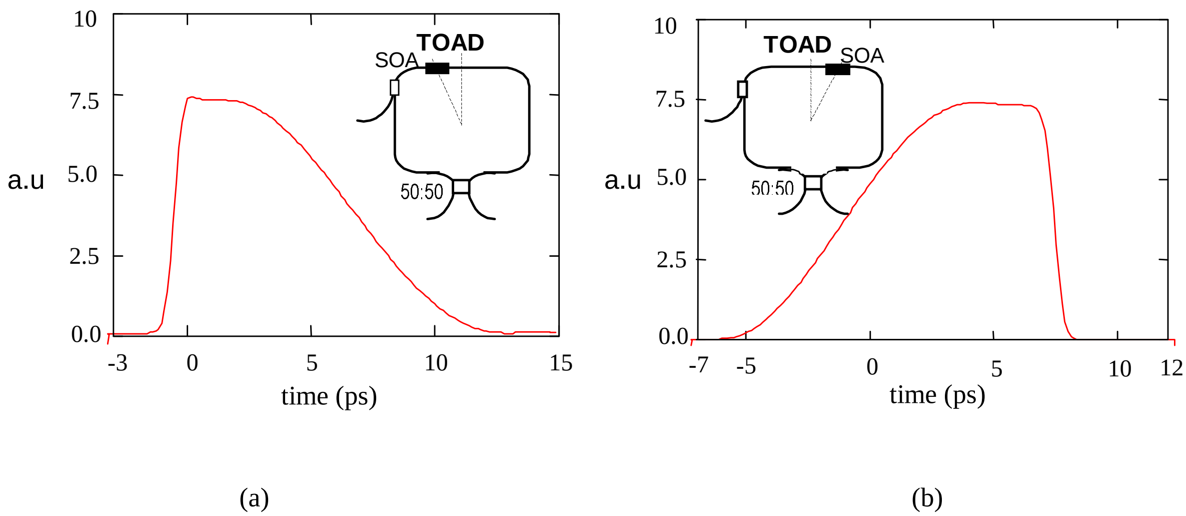

Fig 1: The switching windows with the SOA on (a) same side as the control port (b) different side as the control port

The transfer function of one TOAD can be written by the basic interferometric equation [17]

$$SW(t) = \left\{ G_1(t) + G_2(t) - 2\sqrt{G_1(t)G_2(t)}\cos(\phi_1(t) - \phi_2(t)) \right\} \quad (1)$$

where $G_1(t)$, $\phi_1(t)$ and $G_2(t)$, $\phi_2(t)$ are the time dependent gain and phase changes experienced by the two counterpropagating pulses as they traverse the SOA. By cascading the two TOADs with a time shift of δ between the two windows, the overall transfer function referred to as *Cascade* (t, δ) becomes the product of the two constituent ones, $SW_A(t)$ and $SW_B(t)$ with the time shift taken into account.

$$Cascade(t,\delta) = SW_A(t) \times SW_B(t-\delta) \quad (2)$$

In such a configuration, one TOAD has the SOA on the same side of the loop as the control port and the other has the SOA on the opposite side of the loop as the control port. Their switching windows are then placed such that the sharp edge of each overlaps the sharp edge of the other, as shown in figure 2, and this results in a switching window size limited only by the optical pulse width of the clock and data.

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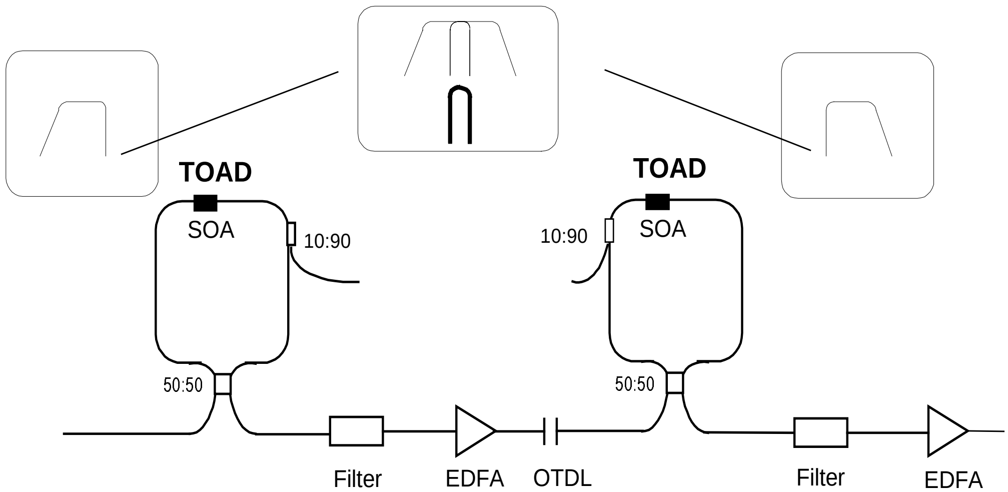

Fig 2 The principle of the optical switch based on overlap of two switching windows

Thus, in comparison with the individual switching windows of figure 1, the cascaded TOAD has its switching window's falling and rising edges determined by the sharp edges of the two individual windows. The slow falling and rising edges of the two individual TOAD windows, limited by the propagation time of the pulses in the SOA, do not affect the switching window of the cascaded TOAD.

To study this effect, simulations were done using a model for the gain and the phase changes, based on previous work [17]. The simulation uses Gaussian pulses with 1ps width for input clock and 1.5 ps width for the input data. The SOA is taken as 500 μm long with a 200ps recovery time. Figure 3 shows the simulated switching window of one TOAD for different SOA offsets. As the SOA is moved from one side of the loop to the other, the rising and falling edges are interchanged. In figure 4, the switching window of the cascaded TOADs is simulated with different delay offsets δ, between the two windows each of which are 8ps wide. The switching window amplitude remains fairly constant until the width is decreased to 1.4ps.

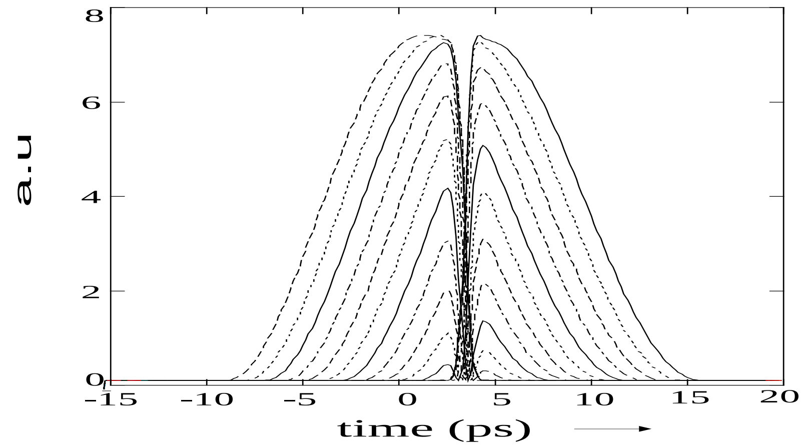

Fig 3: The simulated switching window of a TOAD for different SOA offsets

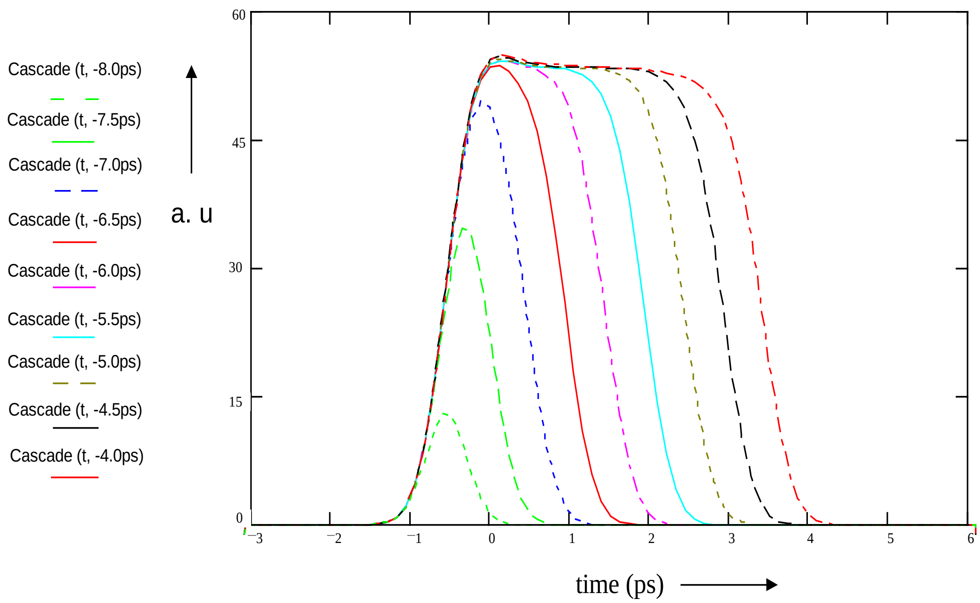

Fig 4: The simulated switching windows with different delay offsets δ between the two TOADs

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3. Experiments and results:

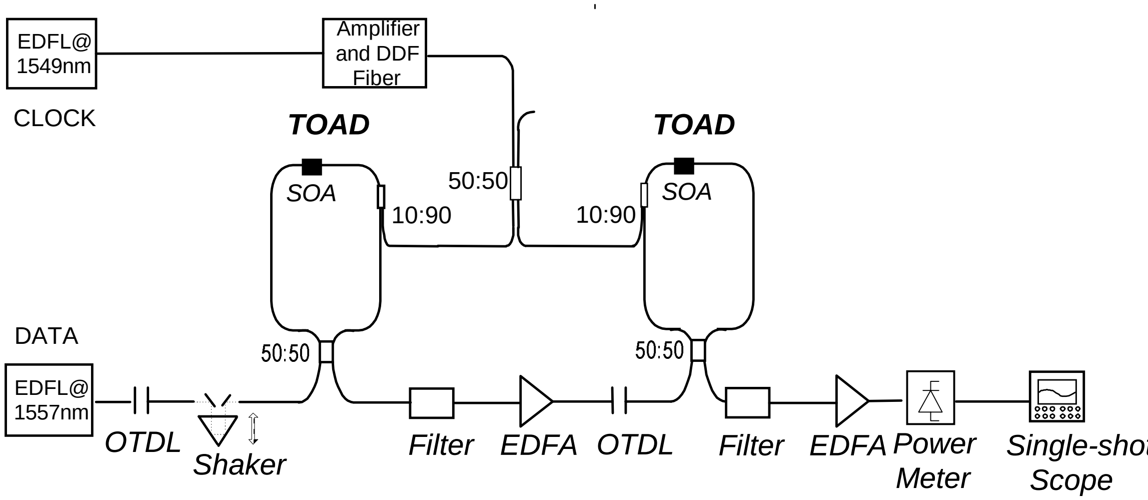

Fig 5: The experimental setup to measure the switching window of the cascaded TOAD

EDFL: Erbium Doped Fiber Laser, OTDL: Optical Tunable Delay Line, DDF: Dispersion Decreasing Fiber

EDFA: Erbium Doped Fiber Amplifier, SOA: Semiconductor Optical Amplifier

The experimental demonstration, shown in figure 5, uses two TOADs, each with an 8ps switching window but with the SOA on opposite sides of the fiber loop with respect to the control port. Two mode-locked Erbium Doped Fiber Lasers are used as clock and data pulse sources. The SOA used in the experiment is a 500µm long Alcatel 1901 SOA biased near 100mA. The clock pulses have a wavelength of 1549nm and pass through an amplifier and dispersion-decreasing fiber, which compresses the pulse width to 1ps. The data pulse width is 1.5ps and the wavelength is 1557nm. Prior to entering the first TOAD, the data pulse first passes through a free space delay stage and a mechanical shaker. The free space delay stage positions the temporal position of the data in the range of the switching window of the cascaded TOAD. The mechanical vibrator is used to quickly scan the data pulses in time over a 30ps range to map out the switching window. By continuously monitoring the switching window on the oscilloscope, this technique provides a means of rapidly characterizing the switching window [18]. After the mechanical vibrator, the data pulses enter the first TOAD. The data pulse then exits from the output of the first TOAD and passes through a filter, an EDFA and a tunable free space delay line, before entering the second TOAD. The filter rejects the clock pulse of the first TOAD from entering the second TOAD. The tunable delay line between the two TOADs controls the temporal position of the second TOAD's switching window relative to the switching window of the first TOAD, and thus provides the control over the aggregate switching window size of the two cascaded TOADs. The output of the second TOAD first passes through an optical filter to reject the clock pulse before entering a power meter. The power meter is connected to a single shot oscilloscope that is synchronized to the mechanical shaker. The switching window size can be inferred because the oscilloscope displays the convolution of the data pulse with the switching window of the cascaded TOADs.

Figure 6 shows experimental scan of the switching windows of the cascaded TOADs for different delay times δ between the two TOADs as it appears on the single shot sampling scope. The shape of the experimental switching windows differs from the simulated ones.

This could be due to experimental non-idealities like variation in control pulse energy and slight variations in coupling losses of the mechanical vibrator used to scan the data signal through the switching window. Also, the simple simulation model may not adequately take into account other physical device level effects that may influence the switching behavior.

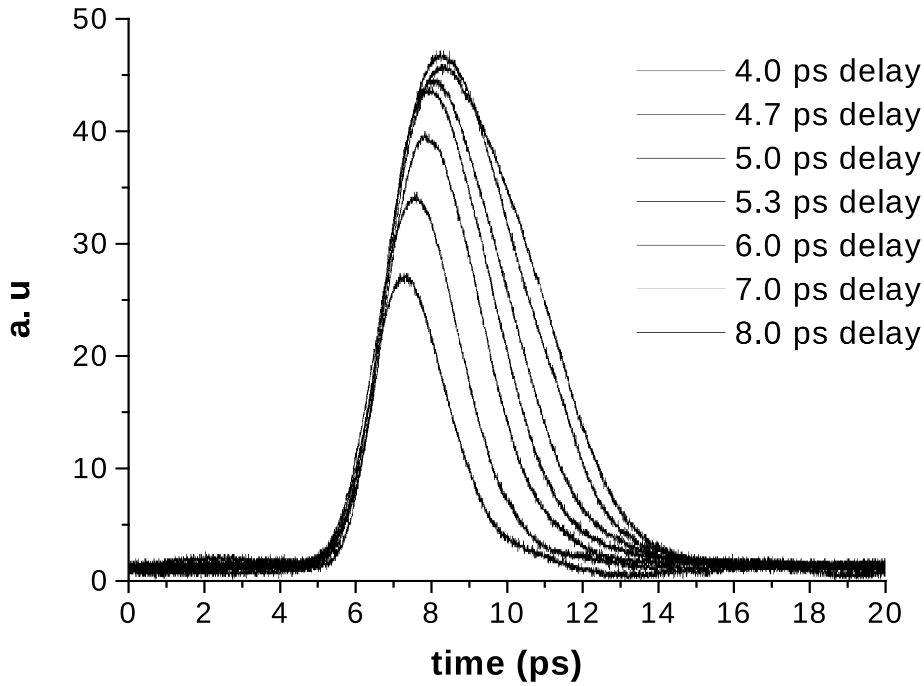

Fig 6: Experimental data, showing the switching windows convolved with the data pulses, for different delay offsets δ, between the constituent switching windows

The experimental windows shown in figure 6 represent the convolution of the 1.5ps data pulses with the actual cascaded TOAD switching window. The actual switching window size can be inferred by de-convoluting the measured switching window with a 1.5ps pulse. We compare the actual switching window widths obtained theoretically and experimentally as a function of δ, the delay offset between the two TOADs, in figure 7. We also show the switching windows obtained after de-convolution with the data pulse. The difference between the experimental and de-convoluted experimental switching windows increase as the switching window becomes smaller. The cascaded TOAD switching window is also limited by the input clock pulse width; this is evident in the decrease in switching window amplitude when the window width narrows to less than 2.9 ps.

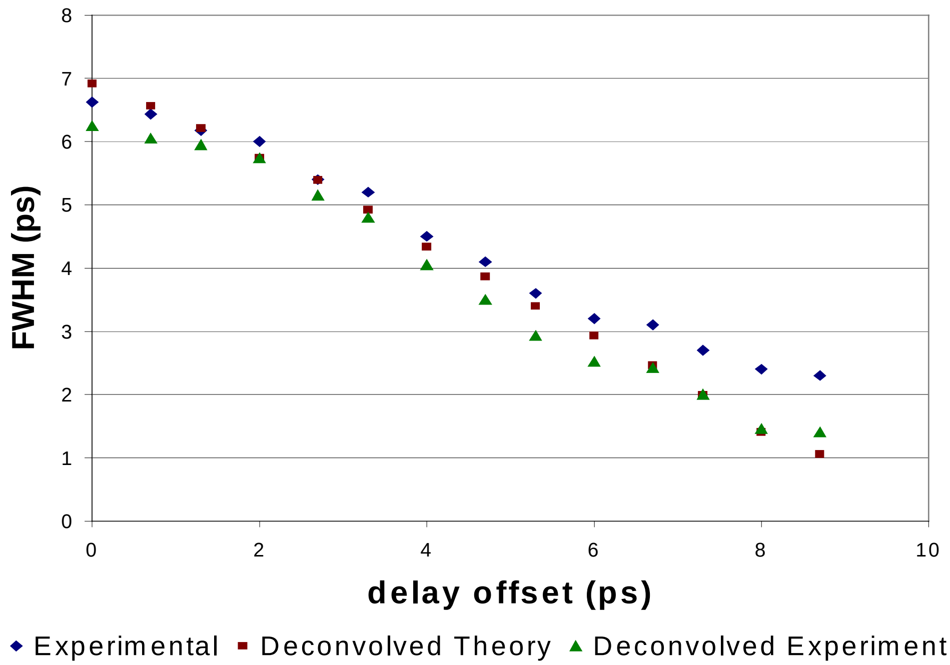

Fig 7: The full width half maxima of the experimental, theoretical and de-convoluted experimental switching windows with different delay offsets, δ

4. Discussion:

Presently, one of the best performing interferometric fiber-based optical switch geometry is the Symmetric Mach-Zehnder (SMZ) geometry [16], and we compare the performance of the cascaded TOAD to the CMZ. The SMZ requires stringent polarization control as thermal fluctuations can offset the interference conditions between the two arms [18]. The cascaded TOAD is immune to thermal effects in the laboratory because the two counter propagating pulses in each TOAD travel through the same span of fiber. However, one advantage that the SMZ structure enjoys over the cascaded TOAD is that the SMZ can be easily integrated onto a single photonic chip. Various wavelength converters and 3R regenerators have already made use of this and similar structures [19,20]. The integration of the cascaded TOAD is presently a difficult problem yet to be solved.

The drift in delay offset between the two individual TOADs due to thermal fluctuations can lead to slight variations in overall switching window size. However, this is of the order of few femtoseconds and is negligible compared to the overall switching window size, which is of the order of picoseconds. For constant switching window size, the delay line between the individual TOADs can be replaced by fusion spliced fiber lengths. This will reduce the losses incurred by the signal on passing from one TOAD to another, resulting in higher switching contrast ratio.

The overall switching window depends only on the extent of partial overlap between the two switching windows and not on the relative sizes of the individual windows. However, it is necessary to ensure that the smaller window does not fall completely within the larger window, in which case the overall switching window will be the same as the smaller window and will be limited by the propagation time of pulses in the SOA. Hence, the cascaded TOAD

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gives the same characteristics for different relative locations of SOAs in the loops, when the overlap is partial.

In summary, we demonstrated a novel switch based on two TOADs by utilizing the switching window characteristics of each to achieve a narrower temporal switching window output.

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