Using parallel low powered thermo-optic Mach-Zehnder Interferometers to increase modulation frequency.

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Abstract : Recently there have been less attention given to thermo-optic (SOI) Mach-Zehnder Interferometers switches and modulators (MZI's) due to the their slow frequencies relative to their CMOS fabricated counterparts working at higher frequencies using the plasma dispersion effect. Although the speeds of MZI switches and modulators have increased within the last five years currently they have reached a saturation point due to some physical limitations. In our research we have derived a model for a modulator that could overcome some of these physical limitations to increase speed and also have the modulator keep up with increasing modulating frequencies as faster and faster switches are invented. Our current model is estimated to work in lower MHz frequencies attaining the highest possible modulation frequencies for thermo-optic modulators while proving that power consumption is lowered significantly.

Development of fast thermo-optical modulation.

Before the development of fast thermo-optical (TO) modulation most switches operated below 10 KHz. In general it can be proved that TO switches can be made faster by reducing the waveguide size. Aalto et.al (2003). There are two competing physical effects that limit the speed of the modulator. The modulator can be made to function faster by thinning the oxide (Sio_2) layer between the heater and the waveguide. This will diffuse the heat into the waveguide much faster and also release heat faster. This is required for a fast modulator. By reducing the thickness of the oxide layer the signal at 1550 nm is dissipated out of the waveguide. As a possible solution, increasing the thermal conductivity around the heated waveguide makes the switch faster but, this will increase the power consumption. This leads to a trade off between speed and power consumption.

In addition to the changing of waveguide structure, to increase the speed, cascaded devices could be used. The tradeoff here is that the extinction ratios of each individual device adds up. A different factor is that, it has been found that faster speeds could be achieved by using square wave modulation than random modulation. As previous research has shown, using random binary modulation increases power consumption. The approach we seek to reduce power consumption is by making trenches along designated areas. Although this alteration of design is not new, we will give a complete theoretical proof and substantiate with a fair amount of simulational results that have not been shown in previous literature.

Recent history of research on fast (TO) switches.

*2003 : T.Aalto et.al : Designed a TO MZI that functioned at 167 KHz, 150 mW, extinction ratio at 17 dB. With random binary modulation, the extinction ratio still remained at 13 dB but the power consumption rose to 590 mW. Notice that this is a three fold rise.

*2003 R.L. Espinola et.al., R.M.Osgood Jr. : Switching power 50 mW, rise time < 3.5 μS corresponding to a switching frequency of 200 Hz.

*2003 Jingwei Liu et. al. : Switching power 145 mW, switching speed 8 μS

*2004 Timo Aalto et.al : 1.5 MHz frequency switch. (fastest so far).

Our proposed design for a high speed modulator.

We used several ideas from the high frequency switches mentioned above to build our original model based on the constraints that these models have in order to produce a high speed low powered TO modulator. We divide our design into two separate sections. In the first part of our paper we show a theoretical proof and simulations of a modified MZI that reduces the power consumption by roughly a half and in the second part of the paper we incorporate this modification to our new parallel MZI high speed modulator. We intend to increase the frequency of the modulator while keeping the low power consumption.

(TO) MZI devices.

A thermo-optic MZI can be used as a modulator by heating one of the arms and changing the index of refraction to produce a phase delay with relative to the other and have them interfere to produce a signal with a varying magnitudes. This would be the conventional TO modulating approach to design a device such as a voltage attenuator (a VOA). If the MZI is to be used to encode a binary signal to a carrier wave, the phase shifting arm changes it's phase between π's (180 degrees) and zero's (0 degrees). Using RSoft BPM software the above two states have been modeled in Figure 1.

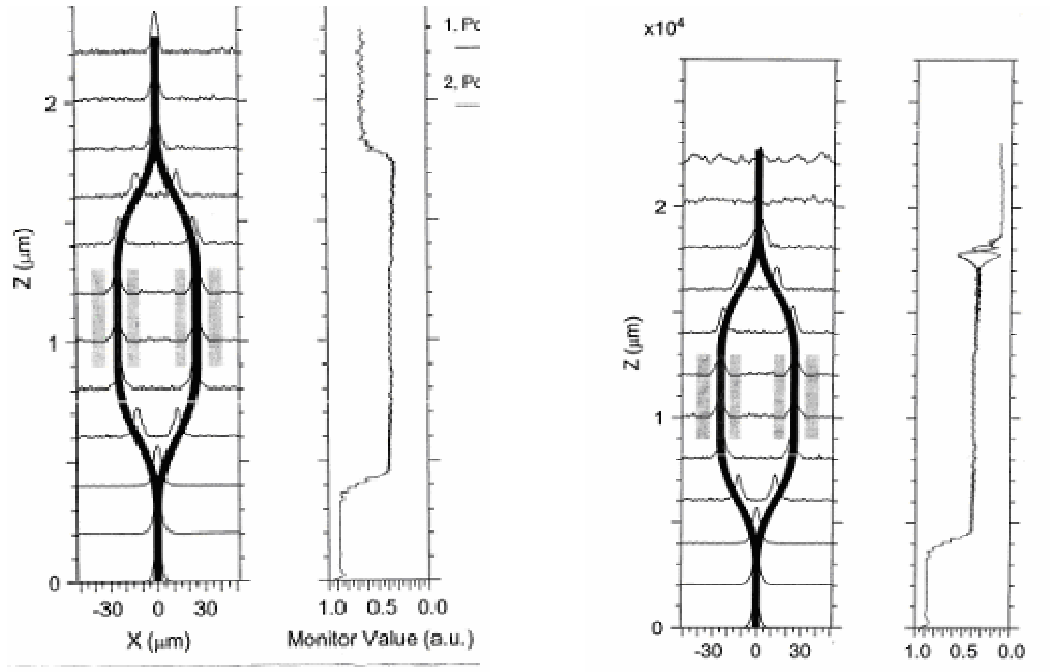


Figure 1. : Signal intensity is given by the graph. Left graph shows a phase change of 0 ; and the right graph shows a phase change of intensity π .

The dissipation of heat to stabilize the temperature into the surrounding temperature is given by :

$$\Delta T = \Delta T_{\infty}(1 - e^{-\alpha t}) \qquad (1)$$

ΔT_{∞} is the difference in room temperature and heater at t=0.
ΔT is the difference in temperature after time t.

In the conventional modulating systems, the multiplier in the exponent of '**α**' plays a significant role on how much the frequency can be increased. Larger the value of **α** the temperature stabilizes faster. Therefore the frequency can be increased. We will show in the second half of this paper how our modulator can increase α by multiples of two or more.

When an electrical current is applied to one of the heaters, the optical phase change in the heated arm can be expressed as,

$$\Delta\Phi = (\partial n/ \partial T). L . \Delta T (2\pi / \lambda) \qquad (2)$$

Where the refractive index change for Silicon is $(\partial n/ \partial T)_{si} = 1.84 \text{ X } 10^{-4} / K$

The absolute change of attenuation from one active arm behaves as
$I/Io = Cos^{2} [\pi / \lambda .\Delta d]$ (3)

From the fundamental principles :
$\Delta d = (\partial n/ \partial T) L . \Delta T$ (4)

temperature change which is needed to induce a phase change of π in the arm is given by the normalized output intensity as a function of temperature set to zero. Therefore for the π phase difference, the following equation is obtained. Given the value of length of the MZI, the temperature required to have a minimum output signal can be calculated. The power required for the corresponding output is calculated below.

$I/Io = Cos^{2} [\pi (\partial n/ \partial T) . \Delta T. L / \lambda] = 0$ (5)

Let us look at an intermediate case where the MZI produces a signal between the two extremes. Since the heat is absorbed into Silicon by heat diffusion, a special case of simplified diffusion equation is solved, which is called the "heat equation". The equation below can be found in most undergraduate textbooks. It is solved to calculate the temperature gradient against distance into the waveguide from the heater.

$\Delta T = (P . \Delta X) / (A . K_{sio2})$ (6)
Substituting the value of ΔT from equation (6) in equation (5).

$I /Io = Cos^{2} [\pi (\partial n/ \partial T) . (P . \Delta X. L) / (A . \lambda. K_{sio2})]$ (7)

It can be seen that the above equation takes the form
$I /Io = Cos^{2} [const. X (Power / Heat diffusing area)]$ (8)

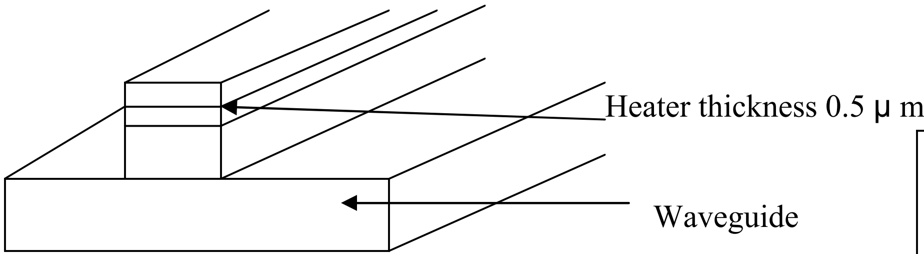
At minimum output power (or maximum attenuation) $I /Io \sim 0$
Solving for the power required to have a phase shift of π is :
$0 = Cos^{2} [\pi (\partial n/ \partial T) . (P . \Delta X. L) / (A . \lambda. K_{sio2})] = Cos^{2} [\pi /2]$
$\pi (\partial n/ \partial T) . (P . \Delta X. L) / (A . \lambda. K_{sio2}) = \pi /2$

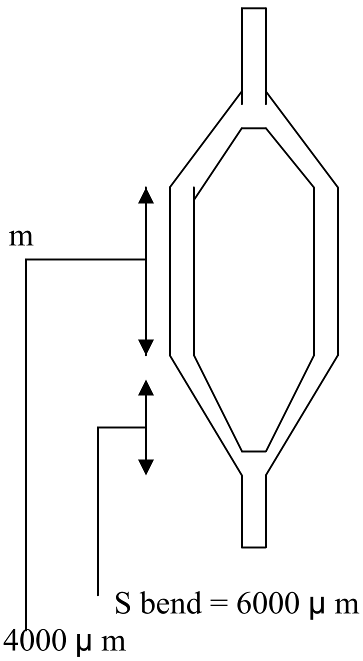
Therefore $P\pi = \lambda/ 2L.(\partial n/ \partial T)^{-1} K_{sio2} .A / \Delta X$ (9)

It can be seen from the above equation :
Pπ is proportional to A and inversely proportional to L . If L (the heater length) is kept constant, then **Pπ α Heat diffusing area**

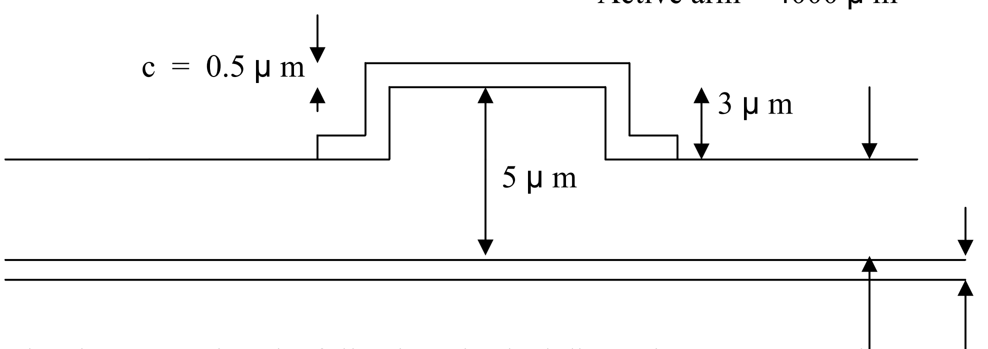
The above result proves that in order to reduce the power consumption either the thermal diffusive area has to decrease or the length has to decrease. But, not both, at the same time.

Choosing an arbitrary MZI :





Using FEMLab simulations for a MZI



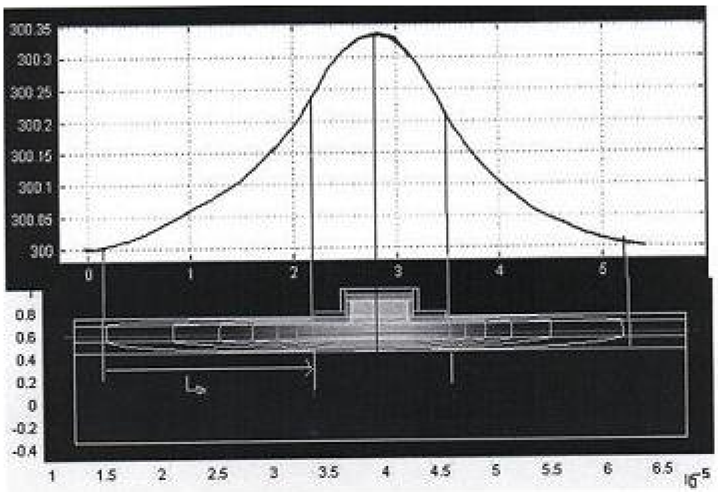
The above MZI has the following physical dimensions.
Active arm Length = 4000 μ m
S bend = 6000 μ m
Heater thickness 0.5 μ m
Waveguide width = 3 μ m
a = 0.5 μ m   b = 0.5 μ m

Before applying equation $P\pi = \lambda / 2L.(\partial n/ \partial T)^{-1} K_{sio2} .A / \Delta X$
the thermal diffusive area is calculated. This is the furthest length from the waveguide arm which the heat diffuses itself (figure ?). In order to calculate area 'A' the thermal diffusion length will be required.

(---------------------------------Optional -----------------------------------)
(------------Deriving the thermal diffusion length L_{th}:)----------------)

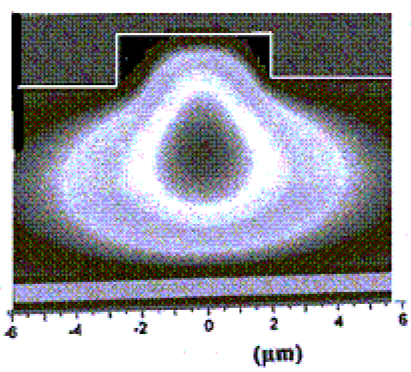
Thermal diffusion length $L_{th} = (\sigma\ si / \sigma\ sio2)^{1/2} . (b.c)^{1/2} = 15.6\ \mu m$

For a waveguide with same dimensions as above, the heat diffusion throughout the cross section of the waveguide to the surrounding area can be simulated using the FemLab software as the figure(?) below shows. It is evident that the furthest distance to which the heat diffuses is given by L_{th} at roughly 17 μ m (close to 15 μ m) as marked by an arrow.

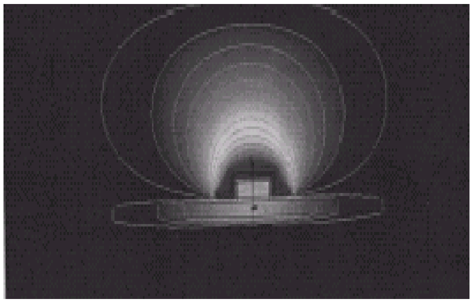


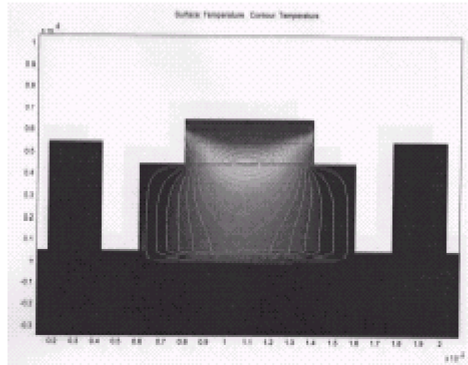
figure(?)

Before we reduce the energy consumption by cutting two trenches along the waveguide it is very important to find out how close to the waveguide these trenches can be placed. By looking at the fundamental mode passing through the waveguide, the minimum distance is determined as the boundary of the fundamental mode.



Figure(?) Fundamental mode.





If the two trenches are cut at 8 μm on both sides of the heated part of the waveguide, FEMLab simulation shows that heat from the heater is confined within the volume where the fundamental mode passes. By using equation (9) power consumption between the two cases are calculated and graphed as below against normalized signal attenuation.

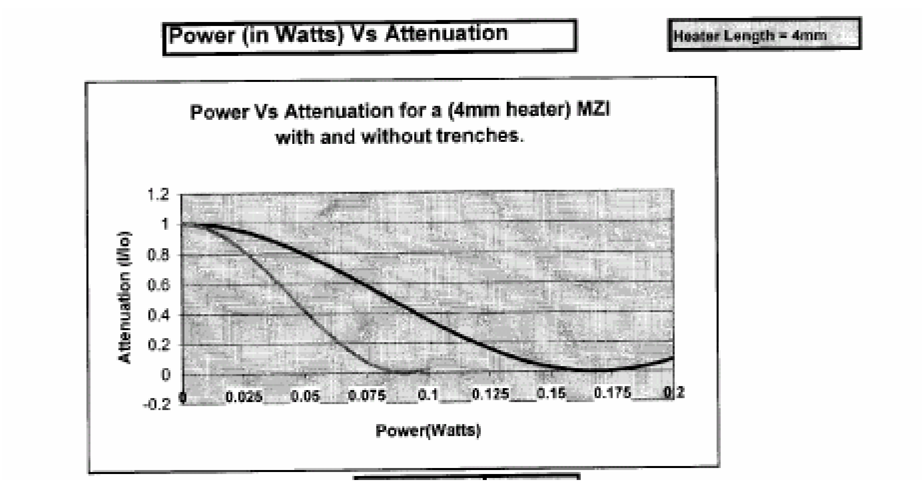


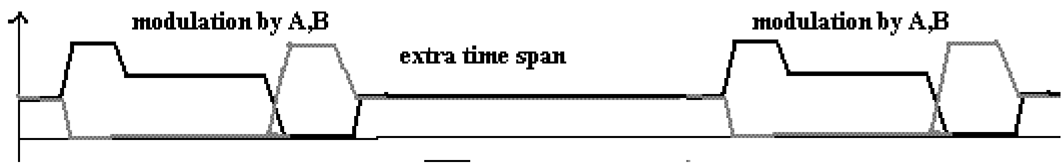
Figure (?) : The graph with the maximum attenuation around 90 mW is for the MZI with trenches and the graph with the maximum attenuation around 175 mW is for the MZI without trenches.

The Modulator

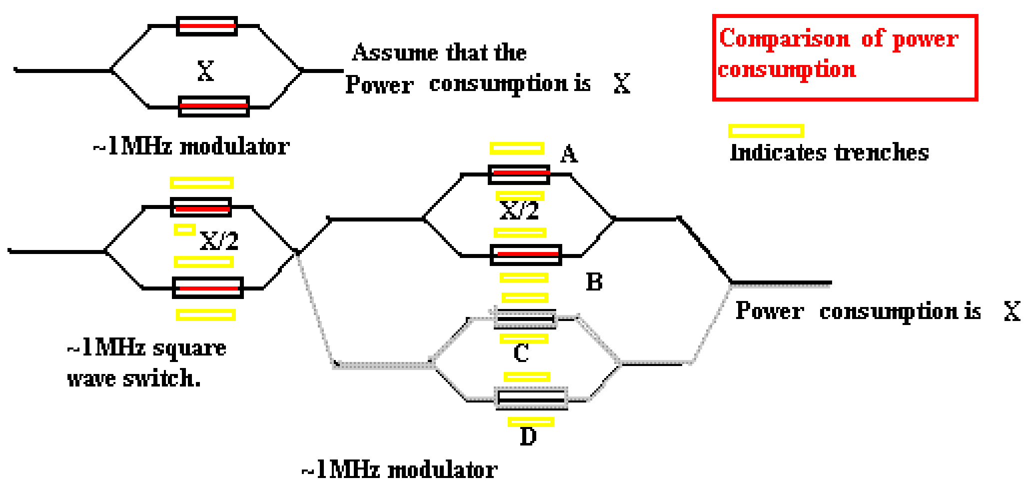
Previously we mentioned some of the work done by researchers around the world on TO modulators. Although they have made great strides in this field there are physical constraints that limit TO modulator designs. In this section we address some of these issues in our original design.

Some of the problems with fast TO modulators.

1. Timing for heat absorption and release has reached it's maximum performance. In our model we will extend the time given to cool down the heater by twice or more. There will be a tradeoff here. That is, do we want to completely cool down the heater after one span is over, within the extra time gap (this can increase the modulation depth) or increase the frequency by twice, depending on the application.



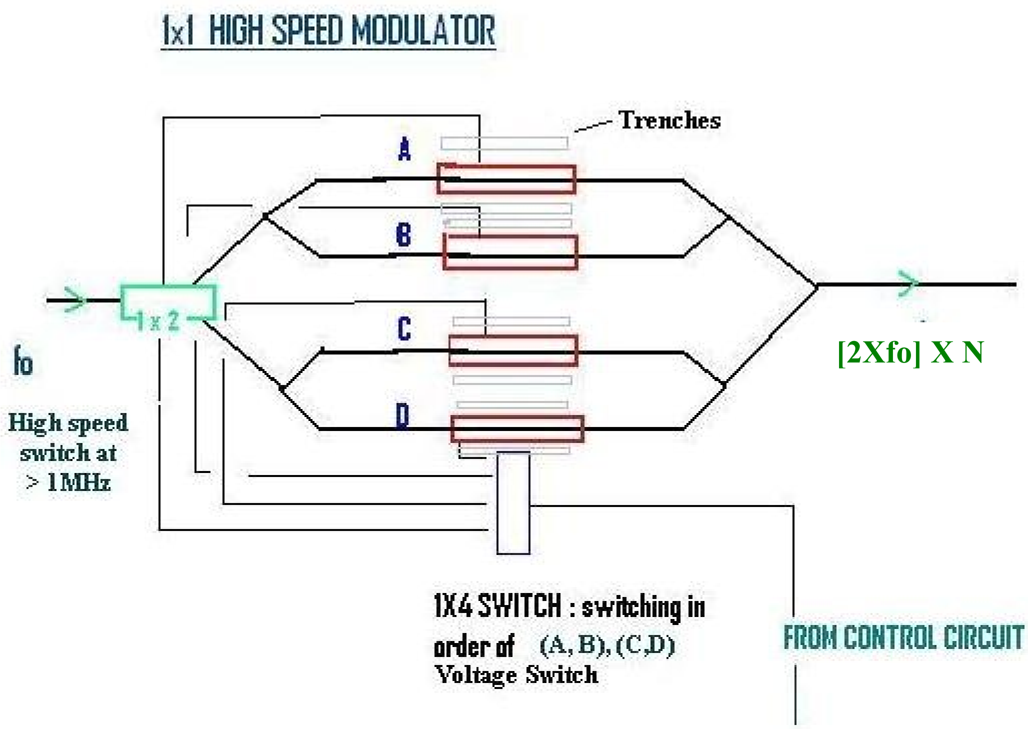
2. Using new modulation techniques in new switches there still remains significant difference in the energy consumption between plain square wave modulation and random binary modulation. The difference could be as much as three times as much T.Aalto et.al 2003. We earlier proved in that the modifications we made to our MZI's by cutting trenches, truncates the power by one half. If we compare the power consumed by the fastest modulator designed, and our design we can prove that they both use the same amount of power while ours is able to increase the frequency.



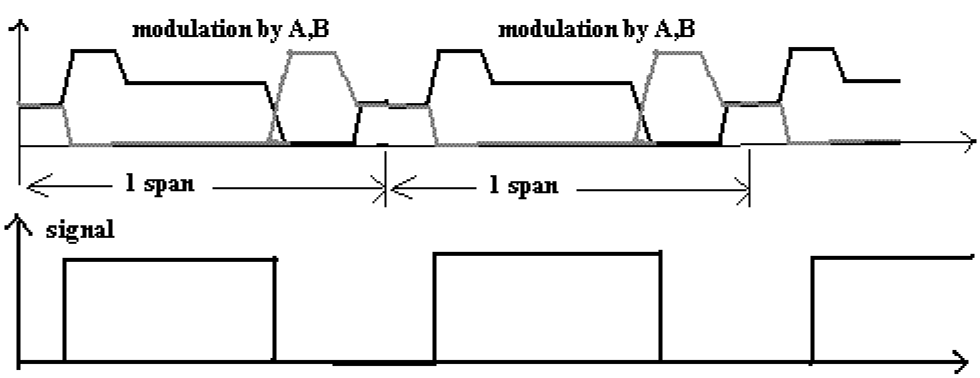
Figure(?) : Assume that the top MZI indicates the design that has been used in developing the fastest modulator using an arbitrary amount of power X. The bottom (1X2 switch + 2X1 MZI's) shows that by reducing the heat diffusing area we can design it such that it uses the same amount of power (X/2 +X/2). At any given time only one arm of the 'cascaded MZI' is being used (colored black).

3. When a random binary signal is modulated (e.g. 101101011111) the heaters operate unevenly. That is one side could gets more one's than zero's. This will form a difference in the stable temperatures, formed by the bias voltages in the two arms of a MZI. This will cause a continuous change in the modulation depth and give out an uneven signal. Therefore having an extra time gap between the modulation span's gives some time to stabilize towards bias voltage temperature.

Our model

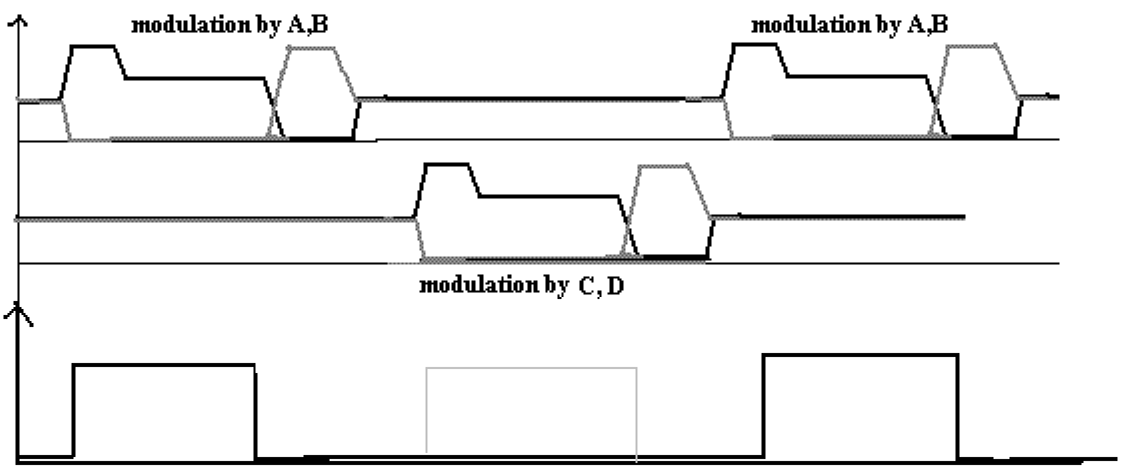


In the previous models when two arms were used for modulation, the following kind of voltage vs. time graph would result for the new differential modulating technique.



square wave signal producing :11111111... for 1 MZI [Case (a)]

When the new modulation method is applied to our model, the following voltage vs. time graph for the two MZI's can be drawn.



Notice that, now that there is a time gap equal to 1 span, between every modulation by the MZI, with arms A,B. This time lag could be used to increase the frequency of the signal by twice or to stabilize the output. By using more MZI's in parallel with 1X4 or 1X8 switches it is possible to increase the frequency of our modulator with the fastest switches (1 X N type) available now and yet to be invented by 2, 4, 8 times or more.