Tuned Attenuation Efficiency of a Silicon Photonic Variable Optical Attenuator with Supplementary Diodes

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Abstract: Supplementary diodes were introduced into a Silicon photonic variable optical attenuator, formed by 4 forward-biased lateral p-*i*-n diodes connected in series, in order to tune its attenuation efficiency.

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1. Introduction

Si photonic variable optical attenuator (VOA) as a new member to the family of electronic controllable VOA has drawn attention and gradually gained market share. Its basic element consists of a forward-biased lateral p-*i*-n diode formed within a ridge waveguide fabricated using Silicon-On-insulator (SOI) material [1-2]. It is fabricated using CMOS compatible processes, which have the potential of disruptive cost reduction given a high volume. A high production volume justifies fabrication at an existing CMOS foundry used to manufacture electronic integrated circuits.

On the device physics side, since the VOA utilizes carrier-photon interaction, it could realize sub-microsecond speed, which is the fastest among existing VOA products in the market. Its high speed lends itself to three unique applications: 1) transient suppression, 2) dynamic channel equalization, and 3) wavelength tracking [3]. For these applications, the VOA is usually used in a closed loop.

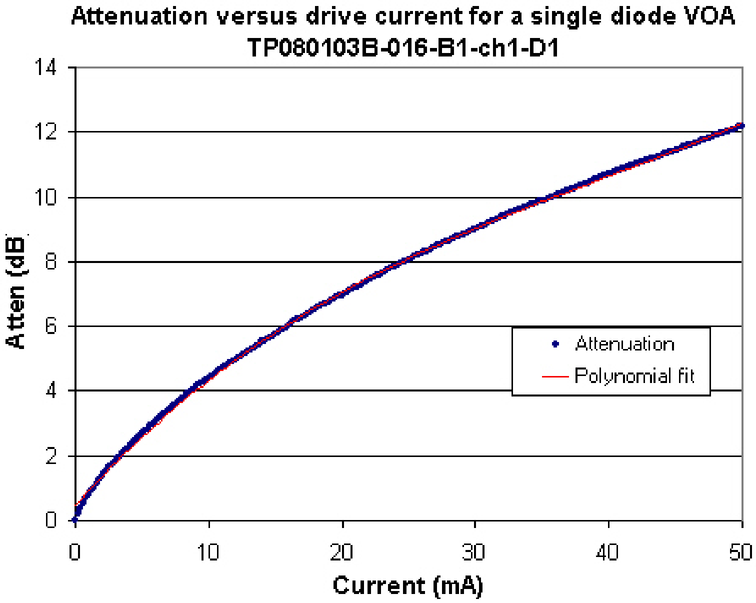

Fig.1 Attenuation versus drive current for a single diode VOA.

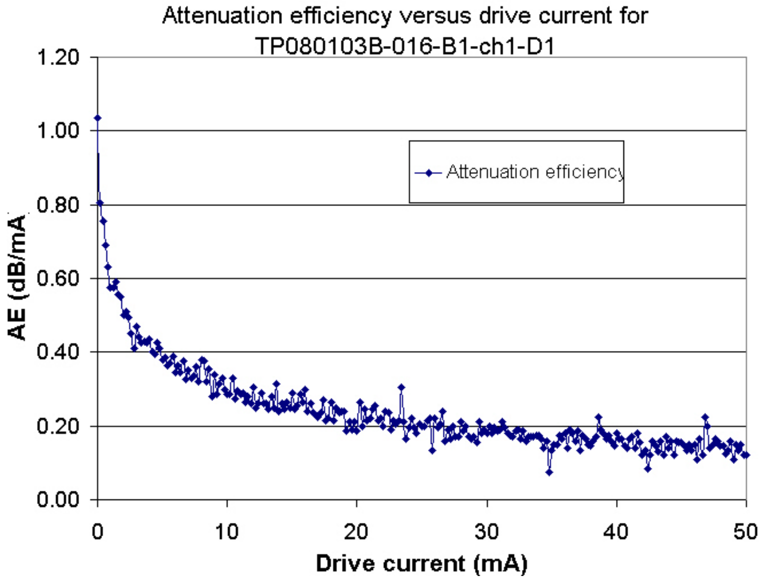

Fig.2 Attenuation efficiency of the device shown in Fig.1 using 0.2 mA as the current measurement step.

From control theory perspective, it is convenient to define attenuation efficiency (AE), which is the derivative of the attenuation versus the drive current, since the VOA is a current driven device. The AE of a single diode VOA spans a large dynamic range from a maximum of 1.2 dB/mA (near zero current – 0 dB attenuation) to a minimum of 0.1 dB/mA (at 40 mA – 40 dB attenuation). The ratio of maximum to minimum AE is 10 to 1 , which makes the closed-loop-control challenging. Figures. 1 and 2 display sample attenuation and AE versus drive current curves for a signal-diode VOA respectively. However, a ratio of less than 3 to 1 is more amenable to a simplified control circuit.

This paper describes a physical mechanism of reducing or tuning the AE at very low current (in a few milli-ampere range) without compromising AE at high drive currents (> 10 mA). We disclose a way to tune the AE of VOA by introducing intentional "leakage" paths that direct current around, instead of through, the optical waveguide.

2. The solution

Practically, the power supply from the line card is usually 5v, therefore 4 p-*i*-n diodes are connected in series to fully utilize the voltage limit. P and N doped regions were laid out along different sides of the waveguide in an alternating fashion as illustrated by Fig.3. Diodes were connected on the Si chip, e.g. the thick red frame outside N1 and P2 indicates that there were metal traces connecting the two regions.

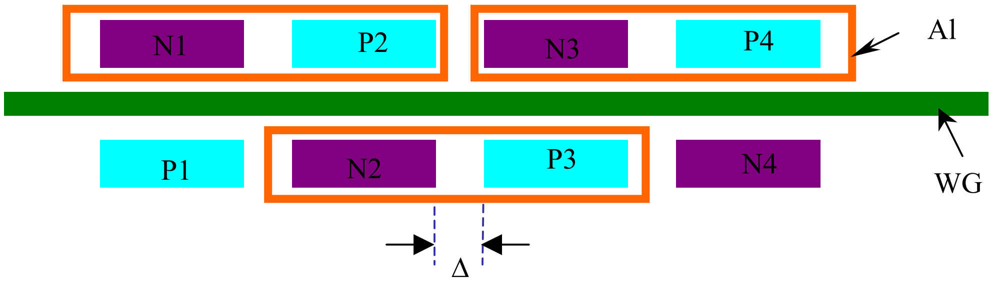

Figure 3 Layout schematics for P and N doped regions (not drawn to scale)

Naturally, we would put isolation trenches between neighboring P and N regions residing on the same side of the waveguide, they are P1/ N2, P2/N3, and P3/N4, so that no leakage will flow through these supplemental diodes. It is straightforward to realize that AE of such a device would be 4 times of the curve shown in Fig.2. As a consequence AE range will span from 0.1 to 1.1 dB/mA, which exceeds the specification we set forth at the beginning.

What would happen if there were no isolation trenches existed between neighboring P and N regions on the same side of the waveguide? The distance between the near-edge of the P and N regions forming the main Pn/Nn (n=1,..4) diodes is on the order of 10 µm, it affects the optical and electrical performances of the VOA. The optical mode is confined by the ridge structure so the doped P and N region on the two sides can't be too close, otherwise they will overlap with the light and causes optical loss. They can't be too far either, obviously the farther the distance, the higher the power needed to reach the same attenuation level. However, we have the freedom to choose the width of inter-diode gap marked Δ, shown in Fig.3. It is straightforward to realize that currents going through those supplemental diodes, namely P1/ N2, P2/N3, and P3/N4, will reduce the amount of current passing through the main Pn/Nn (where n is an integer), and make no contribution to the attenuation. The existence of these leakages currents would reduce the attenuation efficiency of the main diodes, which is something we are looking for. Precisely speaking, what we need is to leak a small amount of current at low drive current and negligible amount of current at the high drive current.

The supplemental P1/N2 diode is basically a lateral p-*i*-n diode, oriented 90º from the main diodes. Intuitively, we know from the device physics, a wider gap of Δ, i.e. a longer intrinsic region would lead to less response current at a given bias, therefore if this diode gap could be properly selected, it will generate the tuning effect we want. Experimentally, the gap Δ was varied from 100 to 400 µm with 100 µm as the step size. The effect of this gap on attenuation is found in Fig. 4. Realistically, 100 µm gap led to too much leakage current and loss of attenuation efficiency.

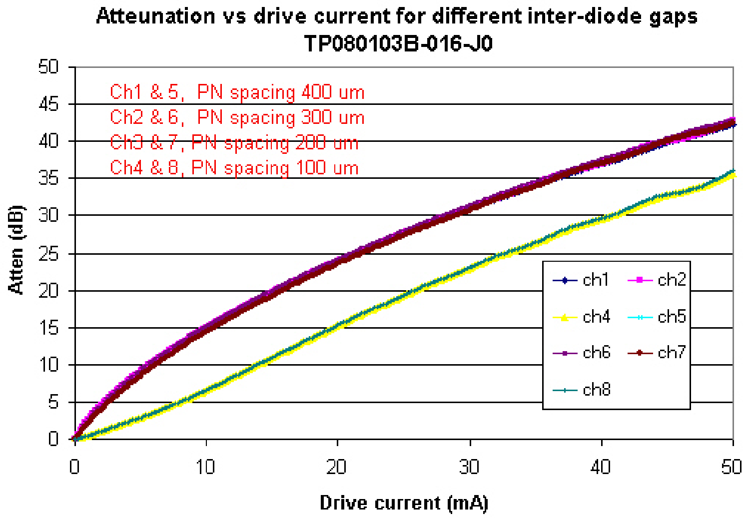

Fig.4 Attenuation of VOAs with different inter-diode gaps versus the drive current.

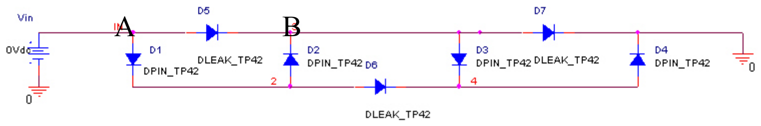

Fig.5 A schematic circuit diagram showing all components in a VOA.

3. The model

An equivalent circuit of the VOA with 4 main diodes and 3 supplementary diodes is drawn as Fig. 5. Referring to Fig. 3, when a positive bias is applied between P1 and N4, each supplemental diode, namely D5, D6, and D7 in Fig.4, is also positively biased, and each of them is competing with 2 main diodes in series. For example, the voltage drop between diodes D1 and D2 also applies onto D5. Since the supplemental diodes have larger turn-on voltage and higher ideal factor, the percentage of supplemental current will drop drastically as the total current increases. The main diodes are about 10 μm wide in the direction perpendicular to the waveguide, and thousands of microns in the direction parallel to the waveguide, it is rationale to model it using a 2D device model. However, the supplemental diode P1/N2 is not two-dimensional devices, therefore, it is easier to measure the I-V behavior of each supplemental and main diode, put them into a SPICE model and predict the relationship between attenuation versus total drive current I_t.

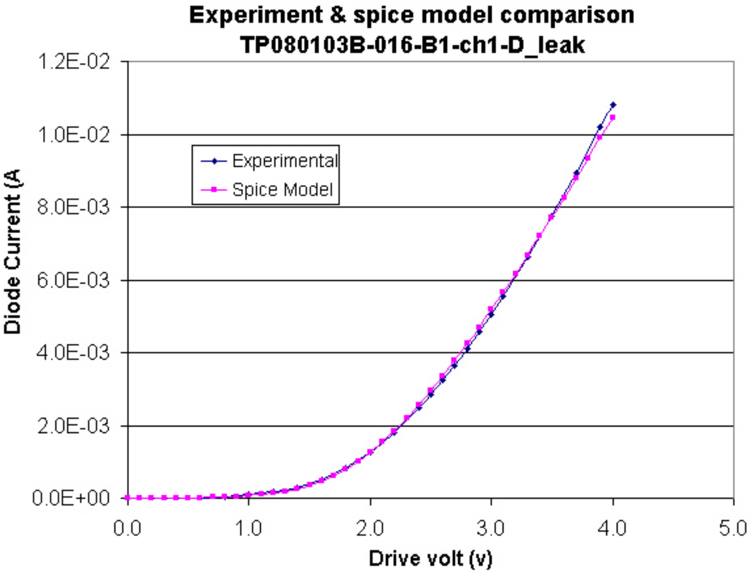

Fig.6 Measured and modeled I-V curve of the leakage diode

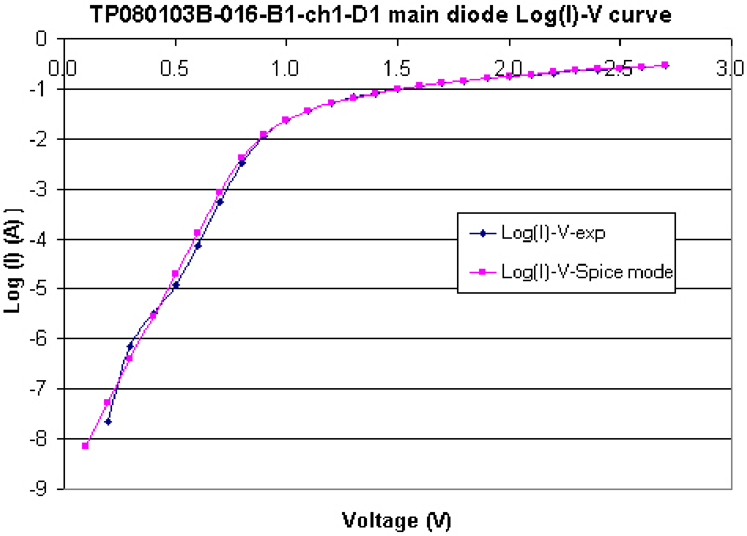

Fig. 7 Measured and modeled Log(I)-V curve for the main diode.

The most convenient way to get the supplemental diode I-V behavior is to measure the main diode I-V, i.e. D1 and D2 in Fig. 5, and measure the I-V between points A and B, and extract the behavior of D5. After getting the behaviors of main diodes and supplemental diodes, they could each be modeled using SPICE2 parameters. SPICE model reproduced I-V curves for the case of Δ=200 µm are plotted against corresponding experimental values in Figs. 6 and 7 for the supplemental and main diodes, respectively. Therefore the relationship between the total current going through the VOA and the current going through each main diode could be established. After the attenuation versus drive current curve is measured for each main diode, and they are practically the same for all 4 diodes within a VOA, the total VOA attenuation versus total drive current behavior could be predicted. By doing this, we could avoid measuring the attenuation of each VOA corresponding to different gap Δ, which requires the tedious processes of optical facet polishing and testing. Fig. 8 presents a comparison between a predicted and measured AE for a VOA device. Note the optical attenuation of a single diode VOA and the I-V behavior of all diodes were measured in Channel 1 of a die, but the experimental attenuation versus driver current relationship was measured from Channel 4 which is 750 µm away in a VOA array. Note that we have successfully predicted the shape of the AE versus drive current shape, which went up at low current, and dropped after a peak was reached. However, the peak position and value were a little bit off which seemed to be that the leakage current was over-estimated in the model at low bias. The drive current range was plotted between 0 and 25 mA so that the low current end could be seen more clearly.

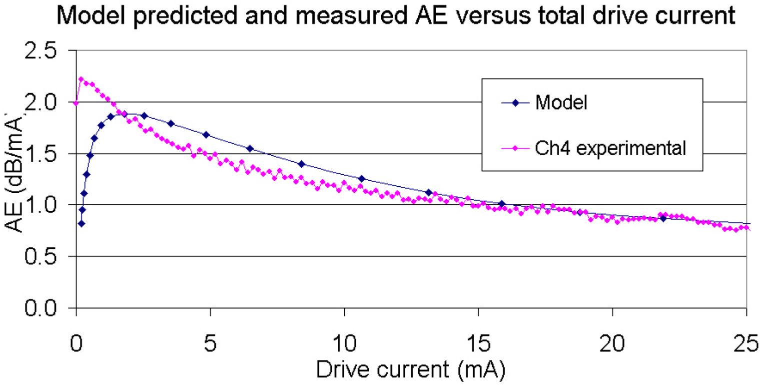

Fig.8 Model predicated and measured Ae versus VOA drive current

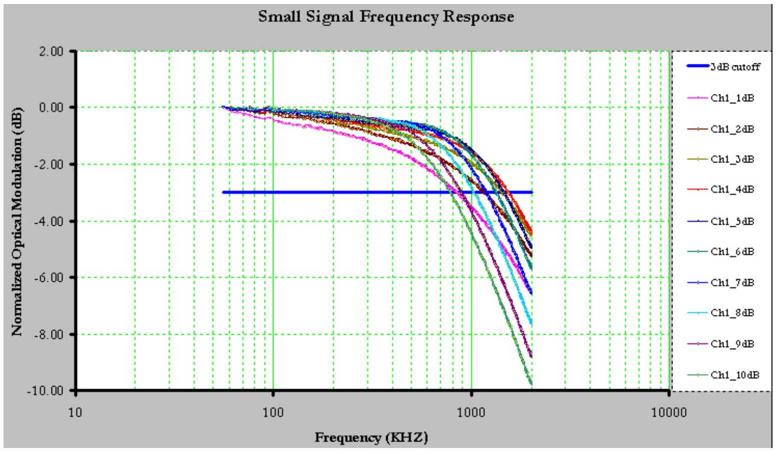

Fig.9 3dB bandwidth measurements of VOA under different DC bias.

As stated in the introduction, not only DC but also AC and transient behaviors of the VOA are of application interests. Fig.9 shows the small signal modulation 3dB bandwidth measurement of a VOA under different DC biases, indicated by different levels of DC bias induced attenuation. If we plot the 3dB bandwidth versus drive current, we can see it follows the same trend of AE, which increases at low current and drops after reaching the peak.

4. Conclusions

In summary, we presented a way to tune the attenuation efficiency in a VOA by introducing supplemental diodes that control intentional leakage currents. A SPICE model was used to explain the experimental observations. The impact on attenuation efficiency and AC small-signal bandwidth were discussed.

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5. References

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