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Analog Logarithmic Computing Primitives with Silicon Photonics

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Abstract: Optical computing accelerators help alleviate bandwidth and power consumption bottlenecks in electronics. We introduce an approach for the implementation of logarithmic-type analog primitives in silicon photonics.
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1. Introduction

An explosion of data generation and storage in recent years, also known as big data, the demand for novel computing paradigms is more than ever before. An uptake in analog computing [1], and hardware accelerators such as video encoders and neuromorphic chips [2] for machine learning are indications of this demand. Among emerging technologies, optical computing is a promising approach to analog data processing, particularly because of the low loss and huge bandwidth achievable with photonics, leading to high signal-to-noise ratio and enormous parallelization, respectively. In particular, photonic hardware accelerators [3] are proposed to ease the electronic data acquisition and processing impediments as optical co-processors. Similar to the case of optical interconnects, silicon photonics provides a suitable platform for implementation of optical computing devices due to its high compatibility with the current electronic circuits.

Among the analog-computing primitives, the logarithmic function is of importance and is one of the most challenging operations to perform in optics. It could be used as the activation function of neural networks in deep learning, and it is also the building block of the exponentiation function. The lack of logarithmic dependence in conventional optical interactions renders the realization of a logarithm computation block formidable. In this paper, we show an approach to approximate the optical input-output relationship as a logarithmic function by exploiting the nonlinear effects in a silicon waveguide.

2. Logarithm via Two-Photon Absorption

For a quasi-continuous signal with wavelength below silicon band edge, two-photon absorption (TPA) and the induced free-carrier absorption (FCA) are the main sources of nonlinear loss in silicon waveguides [4]. The evolution of optical intensity along the waveguide is described as [5]:

$$\frac{dI_s}{dz} = -\alpha I_s - \beta_{TPA} I_s^2 - \sigma \Delta N I_s \,, \Delta N = \frac{\tau \beta_{TPA}}{2h\nu_0} I_s^2 \qquad (1)$$

where $\alpha = 3$ dB/cm is the linear loss coefficient, $\beta_{TPA} = 5 * 10^{-12}$m/W is the TPA coefficient, and $\sigma = 1.45 * 10^{-21}$ m^2 is the cross section of free carrier absorption. ΔN is the free carrier density at steady state, τ is the free carrier lifetime, and $h\nu_0$ is the photon energy.

The optical limiting phenomenon is observed at high input intensity as a result of the dominant nonlinear loss. Between the linear region and the saturation region, there exists a sublinear curve that resembles a logarithmic function, as illustrated in Fig. 2. The logarithmic region is defined as the largest input intensity range whose output can be fit to a logarithmic function with the required accuracy. As a measurement for the fitting accuracy, the normalized root-mean-square error (NRMSE) $=\sqrt{\left(I_{out} - I_{fit}\right)^2}/(I_{max} - I_{min})$ and the maximum error of single point $(Max\ Error) = max\left(\left|I_{out} - I_{fit}\right|/I_{out}\right)$ are calculated separately.

An example of waveguide with length Z = 2 cm, lifetime τ = 1 ns, and propagation loss $\alpha = 3$ dB/cm is shown in Fig. 2. The signal undergoes degenerate TPA and FCA and is fit to a logarithmic function I_{fit} over the input intensity from 50 MW/cm^2 to 250 MW/cm^2, resulting in 7 dB dynamic range. It is noted that it requires very high input power to reach the logarithmic region. This results from the large ratio between the linear loss coefficient and the nonlinear loss coefficient: the nonlinear term only comes into effect when input intensity is above a certain region. A low propagation loss coefficient and a large free-carrier lifetime would reduce this ratio and shift the logarithmic region to lower input intensity. Unfortunately, a large free-carrier lifetime is not practical because it also reduces device's speed, while ultra-low linear absorption is limited by the fabrication technology. A practical computing primitive thus would require larger logarithmic range, lower power, and more flexibility.

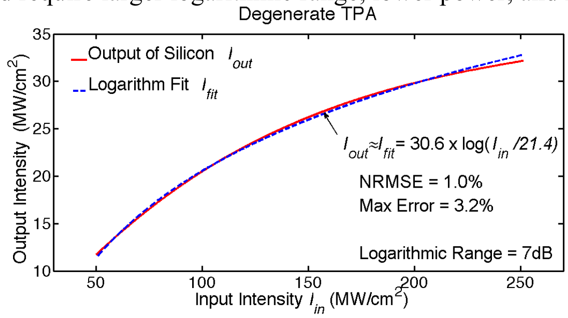

Fig. 1. Numerical demonstration of the logarithmic computing primitive in a silicon waveguide. The signal undergoes degenerate two-photon absorption (TPA) and free-carrier absorption (FCA).

3. Logarithm via Two-Photon Absorption and Stimulated Raman Scattering

Stimulated Raman Scattering offers optical gain in silicon without requiring phase matching [6].At the intensity of signal grows, the pump source is depleted by nonlinear absorption and amplification and the gain becomes less significant. Gain saturation modifies the input-output curve and expands the logarithmic region.

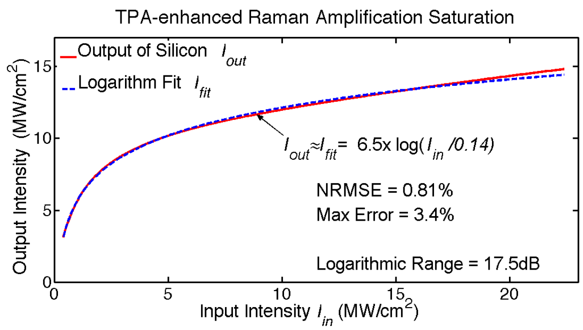

Fig. 3. Similar to Fig. 2, a simulation of the logarithmic computing primitive wherein Raman amplification along with concomitant non-degenerate TPA is added to increase the dynamic range and vastly reduce required signal intensity.

A numerical sweep of the input pump intensity shows that at 48.5 MW/cm^2, the input logarithmic range is further expanded to 17.5 dB, from 0.4 MW/cm^2 to 22.4 MW/cm^2, as shown in Fig. 3. A 10.5 dB logarithmic region for signal input from 0.035 MW/cm^2 to 0.4 MW/cm^2 is achieved when the input Raman pump is 91 MW/cm^2. The introduction of the amplification significantly reduces the power requirement on the signal power, and also increases the logarithmic range. The Raman pump expands device flexibility, allowing one to trade higher Raman pump intensity for lower signal power and a larger logarithmic range.

4. Conclusion

We show an approach to creating the analog logarithmic primitive in by exploiting the nonlinear effect in silicon photonics The component serves as a building block in the photonic hardware accelerator, which is a promising approach to alleviate bandwidth and power consumption bottlenecks in electronics.

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