Signal De-convolution with Analog Logarithmic Computing Primitives in Silicon Photonics

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Abstract: Optical co-processors are proposed as hardware accelerators to take part of the processing burden off of the electron processors. We introduce an approach for the implementation of logarithmic-type analog primitives in silicon photonics and demonstrate its application in signal de-convolution.
Keywords: Analog optical signal processing; Optics in computing; Nonlinear optics.

With the proliferation of big data and the rapid increase in power dissipation of electronics, there is renewed interest in alternative approaches to computing more than ever before [1]. Among emerging technologies, optics offer a particular platform for analog computations, particularly because of the low loss and huge bandwidth achievable with photonics, leading to high signal-to-noise ratio and enormous parallelization, respectively. Contrary to the early attempts at all-optical computing, a hybrid approach where photonic hardware accelerators are proposed to ease the electronic data acquisition and processing impediments [2,3].

Among the analog-computing primitives, the logarithmic function is of importance and is one of the most challenging operations to perform in optics. In this paper, we show an approach to approximate the optical input-output relationship as a logarithmic function in a silicon waveguide via numerical studies.

Stimulated Raman Scattering offers optical gain in silicon without requiring phase matching [4]. Under small-signal conditions, signal I_s is amplified by the Raman pump I_R, and the output increases linearly with the input intensity. When the input further increases, the depletion of Raman pump and the nonlinear loss from two-photon absorption and free-carrier absorption saturate the output intensity [5]. Between the linear regime and the saturation regime, there exists a sublinear region that resembles a logarithmic function. The logarithmic region is defined as the largest input intensity range whose output can be fit to a logarithmic function. To further shape the curve at high input intensity, a new pump source I_P is injected into the waveguide to enhance the nonlinear absorption process through non-degenerate TPA with the signal wave. The evolution of signal wave I_s, Raman pump wave I_R, and non-degenerate TPA pump wave I_P can be modeled as:

$$\begin{cases} \frac{dI_s}{dz} = (-\alpha + g_R I_R) I_s - \beta_{TPA}(I_s + 2I_R + 2I_P) I_s - \sigma \Delta N I_s \\ \frac{dI_R}{dz} = \left(-\alpha - \frac{\lambda_s}{\lambda_R} g_R I_s\right) I_R - \beta_{TPA}(I_R + 2I_s + 2I_P) I_R - \sigma \Delta N I_R \\ \frac{dI_P}{dz} = -\alpha I_P - \beta_{TPA}(I_P + 2I_s + 2I_R) I_P - \sigma \Delta N I_P \\ \Delta N = \frac{\tau_c \beta_{TPA}}{2h\nu_0}\left(I_s^2 + I_R^2 + I_P^2 + 2I_s I_R + 2I_s I_P + 2I_R I_P\right) \end{cases} \quad (1)$$

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 non-degenerate TPA with the third beam I_P suppresses the output signal as the input increases, extending the logarithmic range at the high-input side. For input Raman pump I_R at 56.1 MW/cm^2 and the input non-degenerate TPA pump source I_P at 50.1 MW/cm^2, the logarithmic input range is enlarged to 19.5 dB, from 0.32 MW/cm^2 to 28.2 MW/cm^2, as shown in Fig. 1. Note that the optimized initial pump intensity varies with wavelength due to the nonlinear coefficient's dependence.

One important application of the silicon photonic logarithmic device is for recovery of a signal of interest in the presence of multiplicative distortion. This technique exploits the fact that the logarithm of the product of two inputs is the sum of the logarithms of those inputs. This allows ones to filter multiplicative noise by logarithmic filtering and conventional linear time-invariant filtering. Fig. 2 illustrates this application. As explained in the caption, the logarithm device followed by a linear filter can de-convolve and recover the signal from a mixed composite.

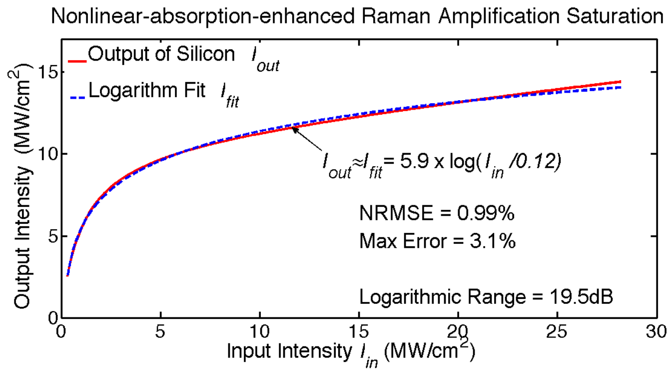

Fig. 1. Synthesis of the logarithmic computing primitive with the nonlinear-absorption-enhanced Raman amplification. The input Raman pump is 56.1 MW/cm2 and the input non-degenerate TPA pump source is 50.1 MW/cm2. The output is fit to a logarithmic function over a 19.5 dB input range with a 0.99% normalized-mean-square error of 0.99% and a 3.1% maximum error.

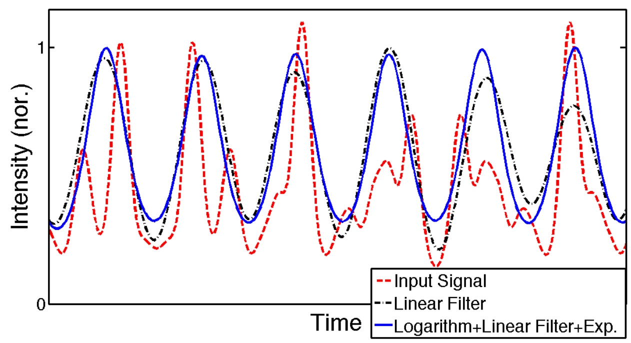

Fig. 2. The silicon photonic logarithm device can perform signal de-convolution. It can be used to recover a signal of interest when it has been mixed (multiplied) by unwanted signal of different frequencies. The Figure shows the composite signal (dashed red) consisting of a single tone input mixed with two unwanted higher frequency tones. Linear filtering (dashed dot black) is unable to recover the input. Logarithm followed by linear filter (and natural exponentiation) is able to recover the input (solid blue). In both cases the linear filter is a 10th order Butterworth.

Exploiting the nonlinear optical properties native to silicon, we show an approach to create a logarithmic analog co-processor in silicon photonics. By engineering the relative strength of Raman amplification and nonlinear absorption, the sublinear relationship between signal input and output is tuned to emulate a logarithmic function. Recovery of signal with multiplicative distortion is demonstrated with the proposed device.

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