Influence of optical amplifiers for on-chip homodyne laser Doppler vibrometers

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Abstract. Photonic integration allows for the development of compact and relatively cheap laser Doppler vibrometers (LDVs). Optical amplification could enhance the performance of these on-chip LDVs, but the intrinsic noise of optical amplifiers could be detrimental for the limit of detection (LOD) of the displacement of the LDV. Recent developments in heterogeneous integration of semiconductor optical amplifiers (SOAs) on the silicon-on-insulator platform allow for compact and relatively cheap development of on-chip LDVs with SOAs. In this paper, we study the influence of an SOA on the LOD of an on-chip homodyne laser doppler vibrometer. We describe the influence of the shot noise and SOA-noise on the LOD of the vibrometer. SOA intrinsic phase noise depends on the optical power in the SOA, causing the position of the SOA to have a large influence on the performance. From the analysis, it is shown that SOAs can improve the performance of an homodyne LDV when there are large losses in the measurement arm. These losses occur due to the coupling of light from the chip towards the target and back into the on-chip waveguides.

1. Introduction

Laser doppler vibrometers (LDVs) are widely used for non-contact measurements of the displacement or velocity of a target. Various applications use LDV for non-contact measurements, ranging from structural health monitoring to remote sound measurements, to different biomedical fields such as non-contact ultrasound, photo-acoustics and cardiology [1], [2]. However, free-space LDV requires bulky and relatively expensive optics, which is a limiting factor for a multitude of applications. Photonic integrated circuits (PICs) allow for the miniaturization of various optical systems. Recently PIC-based LDV systems on the silicon-on-insulator platform (SOI) have been demonstrated [2], [3]. The photonic integration technique enables a compact LDV solution which is important for various applications. Recently, a PIC-based handheld multipoint vibrometer was developed for measuring pulse wave velocities of the carotid artery [2], [3]. In most applications, a low detection limit is desirable or necessary. The detection limit of an LDV depends on several parameters such as photodetector efficiency, electronic bandwidth and the amount of captured reflected light. To enhance the amount of captured reflected light, the transmitting and receiving optics can be optimized. In some applications, a retroreflector on the target can be applied to enhance reflections, but often the use of reflectors is a burden. In the field of biomedical applications, applying a retroreflective tape on human tissue or skin is

a burden or even a potential infection hazard. In situations where the captured reflected light intensity arriving at the photodetectors is low, the signal-to-noise ratio (SNR) of the LDV can drop dramatically. An ideal optical amplification would improve the performance of an LDV. But to estimate the actual performance, the noise sources of the amplifier should be considered. Apart from using an Erbium-Doped Fiber Amplifier (EDFA) in the transceiver system of an LDV chip, recent developments in heterogeneous integration of active components allow for using different semiconductor optical amplifiers (SOA) on silicon [4], [5], [6], [7]. We will focus on the use of SOA-based amplification for PIC-based homodyne LDV on the silicon-on-insulator (SOI) platform. We will discuss the SNR influence for on-chip homodyne LDV for different configurations where the SOA position is changed.

2. PIC-based homodyne laser Doppler vibrometer

Homodyne LDVs have been demonstrated on the silicon on insulator platform [2], [3]. A schematic of such an on-chip homodyne vibrometer can be found in Fig 1.
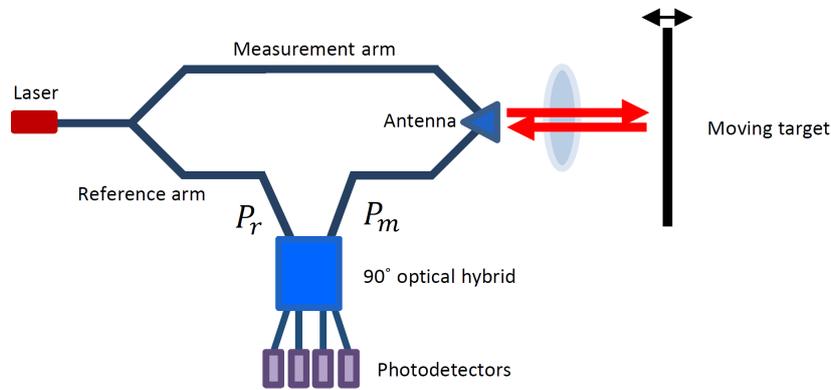

Figure 1: Schematic of a homodyne LDV

As we can see from the schematic, after coupling laser light into the photonic chip, a splitter splits the optical power between a measurement and a reference arm. The light in the measurement arm is coupled out of the chip with some grating couplers and that light is directed towards a target. An optical system can help efficient delivery and collection of light to and from a target. The light reflected from the target is coupled back into the chip. Hereafter, the reflected light is combined with the reference light in a 90-degree optical hybrid. The fields arriving at the hybrid can be expressed through the following phasor notation:

$$\mathbf{R}(t) = E_r exp[i\theta_0 + \theta_{n1}(t)]$$

$$\mathbf{M}(t) = E_m exp[i(\theta_1 + \theta_{target}(t)) + \theta_{n2}(t)].$$

In the formulas above, $\mathbf{M}(t)$ and $\mathbf{R}(t)$ are the fields from the reference beam and measurement beam respectively and $\theta_{target}(t)$ is the phase change due to the moving target. $\theta_{n1}(t)$ and $\theta_{n2}(t)$ represent the phase noise contributions in the reference and measurement arm. Due to the difference in path length from the reference beam and measurement beam, there is an additional static phase in each beam θ_0 and θ_1 respectively. The optical power arriving at the hybrid from the measurement beam and reference beam can be represented as P_m and P_r. The optical hybrid has 4 output ports where the reference light and the measurement light are combined with different relative phases. The phasors of the 4 output ports can be represented as follows:

$$[\mathbf{M}(t) + \mathbf{R}(t)]/2, \; [\mathbf{M}(t) - \mathbf{R}(t)]/2, \; [\mathbf{M}(t) + i\mathbf{R}(t)]/2, \; [\mathbf{M}(t) - i\mathbf{R}(t)]/2$$

Photodetectors at the end of each port convert the intensity into currents. With Eq. 1 and Eq. 2, we can get values which represent points on an IQ-circle (figure 2). In these equations $i_k(t)$ represents the current from port k. Apart from considering phase noise in both arms, a term representing photodetector shot noise is added. The shot noise is a white noise contribution and creates an additional current contribution $i_{shotnoise}(t)$ in the I and Q signal. We assume this additional shot noise current contribution to be a zero-mean gaussian distribution with a standard deviation of $\sigma_{I,shotnoise}$. By demodulation, we can retrieve the phase information of the reflected beam with additional noise contributions from shot noise and phase noise from the arms.

$$I(t) = i_1(t) - i_2(t) = \mu E_r E_m cos(\theta_{target}(t) + \theta_1 - \theta_0 + \theta_{n2}(t) - \theta_{n1}(t)) + i_{shotnoise,I}(t) \quad (1)$$

$$Q(t) = i_3(t) - i_4(t) = \mu E_r E_m sin(\theta_{target}(t) + \theta_1 - \theta_0 + \theta_{n2}(t) - \theta_{n1}(t)) + i_{shotnoise,Q}(t) \quad (2)$$

Here, μ represents the photodetectors' responsivity. If we consider the shot noise (white noise in the output current of each detector), it can be seen that this will cause noise on the demodulated phase, as depicted in figure 2. From the equations above, one can see that the radius of the IQ-circle depends on the power captured by the hybrid.
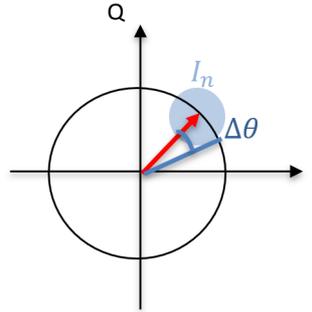

Figure 2: Schematic of the IQ circle with I_n shot noise leading to $\Delta\theta$ noise on the demodulated phase

When the magnitude of the random noise on the currents does not change, increasing the IQ radius results in a smaller noise on the demodulated phase. However, in reality, if the power to the hybrid is increased, the photodetector shot noise is also increased as can be derived from the equation below. In these equations, we assume the shot noise ($\theta_{shotnoise}$) to be much smaller than the IQ-radius. In the equation below, μ represents the photodetectors' responsivity and q the electron charge.

$$\theta_{n,shotnoise} = \frac{\sigma_{I,shotnoise}}{|IQ|} = \frac{\sqrt{4q\mu(P_m + P_r)}}{\mu\sqrt{P_m P_r}} \propto \frac{\sqrt{(P_m + P_r)}}{\sqrt{P_m P_r}} \quad (3)$$

Nonetheless, as we can see from the equations, increasing optical powers can decrease the shot noise contribution to the LDV noise (noise on the demodulated phase). This will be discussed more in the next section.

3. Semiconductor Optical Amplifiers for homodyne interferometry

Assuming a narrow linewidth laser, we can neglect the laser phase noise. Due to the balanced detection explained in the previous part, any intensity noise of the laser or an amplifier can be neglected. In this paper, we will also assume that the electronic circuit is designed such that we can reach the shot noise limit and can neglect the electronic noise sources. In the following analysis, we will thus look at the shot noise contribution and the SOA phase noise contribution to the demodulated phase.

Kikuchi et al. described the different physical mechanisms contributing to phase noise in semiconductor optical amplifiers [8]. Spontaneous emission causes direct phase noise due to emitted light which is out of phase (process 1). Furthermore, the spontaneous emission causes optical intensity fluctuations which induce carrier density fluctuations inside the gain material(process 2). Recombination processes also cause direct fluctuation of the carrier density and thus add to a phase noise contribution (process 3). Eqs. 4, 5 and 6 describe the power spectral density of the different noise sources. We can see that process 1 and process 2 depend on the optical power in the amplifier. Therefore, the position of the optical amplifier in the homodyne LDV is important. For frequencies below $\frac{1}{2\pi\tau_e}$ (which is usually in the 1 GHz region), the power spectra can be assumed flat and will have the following magnitudes:

$$\text{Process 1: } S_{\phi 1} = \frac{h\nu(G-1)n_{sp}}{P_{out}} \tag{4}$$

$$\text{Process 2: } S_{\phi 2} = \left(\frac{2\pi K\Gamma}{\lambda A}\right)^2 4(G-1)n_{sp}\tau_e^2\frac{P_{out}}{h\nu} \tag{5}$$

$$\text{Process 3: } S_{\phi 3} = \left(\frac{2\pi K\Gamma}{\lambda A}\right)^2 2N_t\tau_e \tag{6}$$

The parameters used in these equations are explained in table 1. To simulate an SOA in our homodyne on-chip LDV we will use the values from a traveling-wave GaInAsP optical amplifier from paper [8] as noted in table 1.

Parameter	Symbol	Value
Wavelength	λ	1.52 μm
Internal Gain	G	20 dB
Output Power	P_{out}	variable [mW]
Length	L	500 μm
Cross section	A	0.38 μm^2
Optical confinement factor	Λ	0.57
Spontaneous emission factor	n_{sp}	2
$\frac{\Delta\text{refractive index}}{\Delta\text{electron density}}$	K	$4.10^{-26}m^3$

Table 1: Parameters and Values used for simulation of an SOA. Retrieved from [8]

In this paper, we will consider and compare two different configurations of the amplifier in our homodyne LDV system. In both configurations we assume the optical amplifier to be behind the splitter to limit saturation effects. When looking at the equation estimating the shot noise contribution to the demodulated phase (Eq. 3), one can see that using an optical amplifier after the splitter makes the most sense when there is one arm that has less power compared to the other. In LDV applications, we can imagine that the power of the measurement arm has the most attenuation due small efficiency of coupling light back into the chip after reflection of a

target. We assume this is the origin of the excess loss of optical power in the measurement arm compared to the reference arm. In the following analysis, we will therefore only look at the influence of placing an amplifier in the measurement arm.

In this situation, there are two options; placing the optical amplifier before the antenna and thus before the free space loss or an optical amplifier after the free space loss, as depicted in figure 3. Both situations will have the same improvement of the shot noise contribution to the LDV-noise (if no gain saturation is considered). However, the SOA phase noise contribution will be different due to the difference in power input into the SOA.

In figure 4, one can see an estimation of the phase noise for these configurations. In both configurations, the optical input power is divided equally over the reference- and measurement arm. We assume a power of $100\mu W$ reaches the hybrid from the reference arm. On the x-axis, the excess loss in the measurement arm is plotted. We can assume that this excess loss is mostly due to the in and out-coupling of the light in the measurement arm and the reflection of the target. As can be seen from figure 4a, when the SOA is after the antenna, there is great dependence
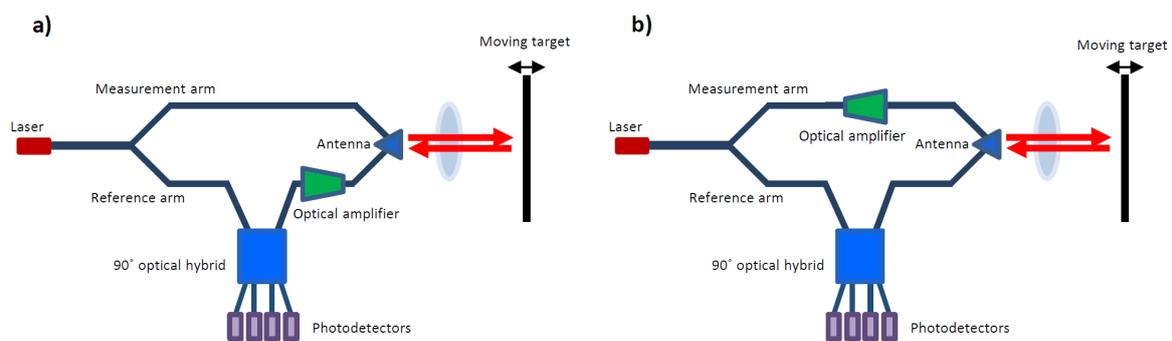

Figure 3: Optical amplifier in measurement arm; a) after antenna and b) before antenna

on the excess loss and it can be seen that for worse excess loss in the measurement arm (= low power into the SOA) the phase noise increases rapidly due to the out of phase spontaneous emission (process 1). On the other hand, when the SOA is before the antenna (figure 4b) the power into the SOA is larger and the phase noise will not depend on the free space losses and thus be constant for different excess loss values, assuming the excess loss originates from free space losses.

Since the displacement detection limit of the vibrometer is linked to the phase detection limit and we will express the LOD as $rad.Hz^{-1/2}$. To estimate if an amplifier could improve the LOD of the vibrometer, we need to compare the shot noise influence on the LDV-noise induced by shot noise to the noise induced by the SOA. When the SOA is in the measurement arm, the SOA phase noise directly translates into LDV-noise (noise on the demodulated phase). The shot noise contribution to the LDV noise can be calculated from Eq. 3. Both contributions are depicted in figure 5. The dotted blue line represents the situation without an SOA (only considering shot noise). This should be compared against the shot noise contribution with SOA (solid blue line) and the SOA induced phase noise (orange line). We can see that placing the amplifier after the antenna does not help a lot to improve the LOD because the SOA phase noise is similar to the shot noise contribution without SOA. However, from figure 5b, one can see that an optical amplifier before the antenna can give an improvement when the excess loss is -20 dB or more. This is when the shot noise contribution without an amplifier is higher than the SOA-induced phase noise, which is the case for high amounts of excess loss. When the excess loss is -35 dB or

(a) Optical amplifier after antenna

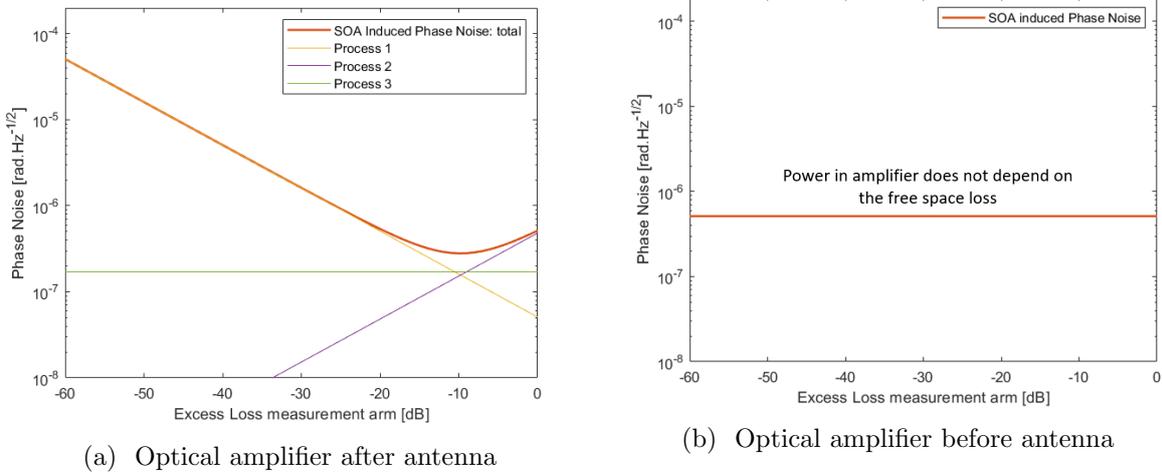(b) Optical amplifier before antenna

Figure 4: Plot of SOA phase noise as a function of the excess loss of the measurement arm when the SOA is in the measurement arm, assuming $P_{ref} = 100\mu W$.

(a) Optical amplifier after antenna
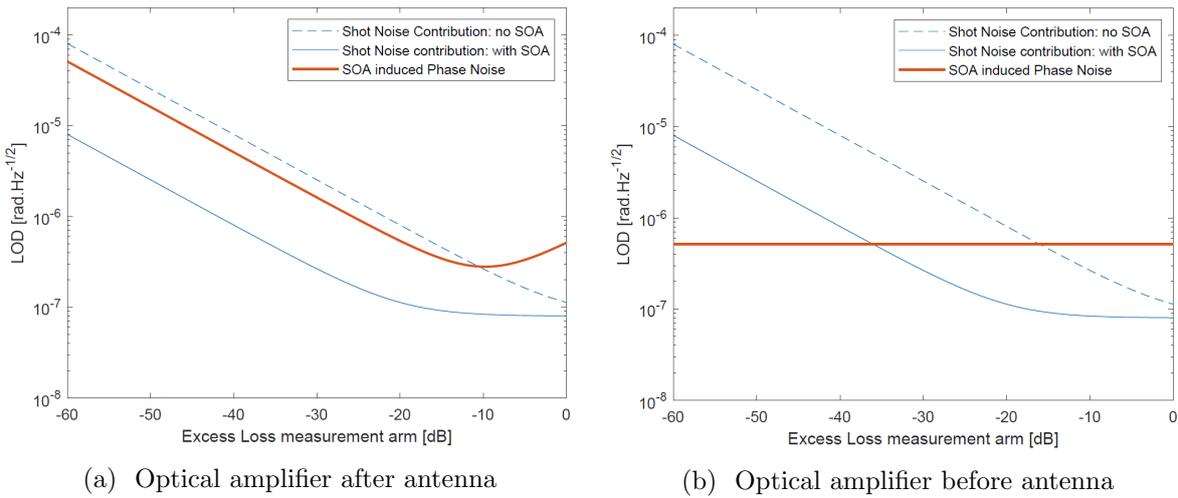
(b) Optical amplifier before antenna

Figure 5: Plot of SOA phase noise and shot noise induced phase noise in function of the excess loss of the measurement arm when the SOA is in the measurement arm, assuming $P_{ref} = 100\mu W$.

more, there is an expected improvement of around 10 dB with the amplifier. Due to the optical amplification, the shot noise contribution is reduced.

From recent results, we estimate the excess loss in the measurement arm to be -15 dB when using a retroreflective tape. For biomedical applications, without retroreflective tape, the captured power would be much lower and we can consider -40 dB excess loss for measurements on skin. With excess losses being that high, the SOA would improve the limit of detection.

4. Optimized Splitting Ratio
In the previous discussion, we only considered equal splitting of the optical power into the measurement and reference arm. In reality, we can use a tunable splitter to control the splitting

ratio $\alpha = S : 1 - S$. S is the fraction of the power before the splitter going into the measurement arm and 1-S represents the fraction going to the reference arm. The shot noise and optical phase noise depend on this parameter and for each situation there is an optimal splitting ratio. In this part, we compare results with optimal splitting. The parameter was optimized through a numerical method. In figure 6 we can see results for an LDV without SOA and an LDV with an SOA in the measurement arm before the antenna. In the figure one can see that an optimized splitting decreases the LOD for both situations. One can also see that an SOA in the measurement arm before the antenna still improves the LOD when the excess loss is lower than around -25 dB.
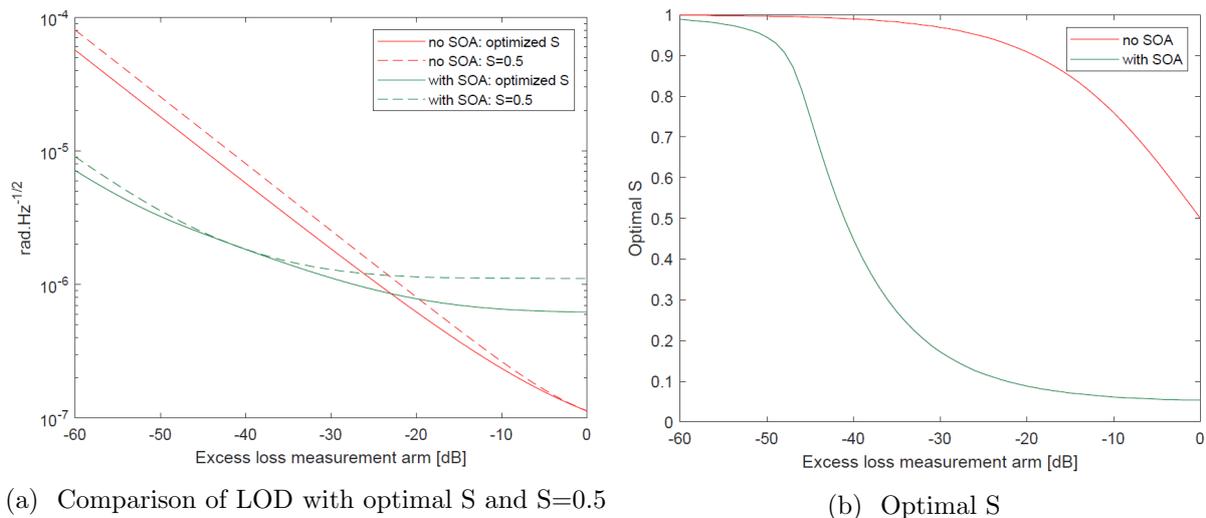

(a) Comparison of LOD with optimal S and S=0.5

(b) Optimal S

Figure 6: Comparison of LDV with and without SOA before the antenna with optimal S.

5. Comparison to Erbium Doped Fiber Amplifiers

From different sources [9], [10], it is found that Erbium-doped fiber amplifiers (EDFA) outperform SOAs in terms of generated phase noise. Generally, the improvement of EDFAs over SOAs in terms of phase noise stays below 10 dB [10] and the actual value depends on the input power. There are however several major benefits of using SOAs for on-chip homodyne interferometry compared to EDFAs. EDFAs generally need an optical pump source to generate population inversion, while SOAs are electronically pumped. This generally allows for cheaper production of SOAs. Evolving techniques (such as transfer printing [4]) allow heterogeneous integration of semiconductor optical amplifiers. This allows for relatively cheap and compact integration of optical amplifiers for on-chip photonic circuits.

6. Conclusion

Semiconductor optical amplifiers can improve on-chip homodyne LDVs, but noise contributions of the SOA have to be considered. In this paper, we numerically estimated on-chip LDV performance for different configurations of combining an LDV with a specific SOA. Due to the increasing noise for low input powers of the SOA, only a marginal improvement of the LOD is made when placing the SOA after the antenna in the measurement arm. In situations where the free space loss is high (-25 dB or worse), placing the SOA before the antenna in the measurement arm gave an improvement. In those situations, the SOA phase noise is lower than the shot noise contribution to the LDV-noise. High free-space losses can originate from a low reflection of the

target and thus is a situation occurring in biomedical applications where no retroreflective tape is used. The optimal splitting ratio of optical power in the reference or measurement arm is changed when using an optical amplifier in the measurement arm. Optimizing the splitting ratio gives an improvement of the LOD. With optimized splitting ratio, using an SOA before the antenna still improves the LOD when the excess loss is lower than -25 dB. The results in this paper are for one specific SOA, but similar trends will be found for other SOAs. Currently, EDFAs outperform SOAs in terms of generated phase noise but SOAs promise to allow for a smaller and cheaper alternative due to the electronic pumping and the possibility for heterogeneous integration. SOAs are an interesting on-chip solution for optical amplification but their phase noise has to be considered when trying to boost the performance of on-chip LDVs.

7. References

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