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Scaling Silicon Photonics-based Laser Doppler Vibrometry with Multi-Beam Frequency Shifters

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***Abstract*—We introduce a multi-beam frequency shifter to enable a scalable architecture for silicon photonics-based Laser Doppler Vibrometers with multiple beams. We show its impact in reducing the amount of electrical connections for high beam-count LDVs on the silicon photonics platform compared to conventional multi-beam architectures.**

I. INTRODUCTION

Silicon photonics-based Laser Doppler vibrometers (LDVs) offer a compact and scalable solution for remotely detecting vibrations in diverse applications, such as non-destructive testing and photoacoustic sensing [1], [2], [3], [4]. In Figure 1a, we show a schematic of a homodyne LDV, which splits incoming light into reference and measurement arms. The measurement light is directed towards the target by a grating coupler and subsequently recombined with the reference light via a 90-degree hybrid. Analysis of photocurrents from four photodiodes facilitates precise target movement demodulation.

However, in practical scenarios requiring the simultaneous detection of vibrations at multiple locations, current LDV implementations are limited, often accommodating only a handful of detection beams as illustrated in Figure 1b. Scaling this technology to support hundreds of sensing beams becomes challenging due to the linear relationship between the number of beams and the required electrical connections or pads on the photonic chip.

This paper proposes an innovative architecture that overcomes these limitations by introducing a multi-beam frequency shifter. We begin by explaining the functionality of this frequency shifter and present simulated performance results. Subsequently, we illustrate how this novel architecture effectively reduces the constraints on the number of electrical connections, enabling the deployment of a large array of LDV beams for advanced applications

II. MULTIBEAM FREQUENCY SHIFTER

A novel on-chip multi-beam frequency shifter design has recently been introduced [5] (Figure 2a), enabling the generation of multiple heterodyne frequency shifts from a single source. This is accomplished by splitting single-frequency light in a waveguide into an array of waveguides, each equipped with a modulator element. Modulation of each element generates harmonics. To separate these distinct frequency shifts, it employs a wave-like modulation pattern across the modulator array, introducing a delay between consecutive modulators. Then, the phase relation of the harmonics at the input of the star coupler allows the collection of these different frequency shifts in various output waveguides. In our discussion, we assume the design of a 16-by-5 frequency shifter, as proposed in [5].

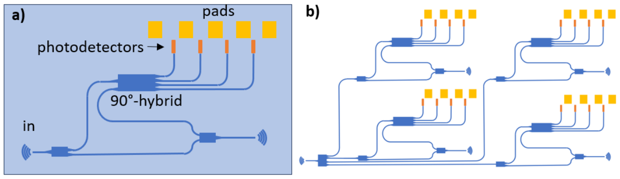

Fig. 1: a) Schematic of an on-chip homodyne LDV. b) Multi-beam implementation of homodyne LDVs

The performance of the multi-beam frequency shifter is calculated by first determining the harmonic content resulting from periodic modulation. Introducing a phase shift between consecutive modulators, we account for the phase modulation induced on each harmonic between adjacent inputs of the star coupler. With knowledge of the amplitudes and phases for each harmonic across all input ports of the star coupler, we calculate the output using the s-parameters of the star coupler. The essential s-parameters are calculated using 2D FDTD simulations, Figure 2c shows this simulation for the upper output. Figure 2b illustrates the different outputs, counted from top to the middle output, demonstrating that distinct harmonics are collected, effectively serving as a multi-beam frequency shifter. The other outputs collect the negative symmetric harmonics and can be deduced from the symmetry. Our calculations assume perfect phase modulation, with a modulation depth of approximately 1.84 and a phase delay between the modulators of approximately 1.25 radians.

III. SCALING TO MULTI-BEAM ARCHITECTURE

The multibeam frequency shifter introduces an alternative architecture for multibeam LDVs on a chip. Figure 1b depicts the traditional approach using multiple homodyne LDVs, where the number of electrical connections scales linearly with

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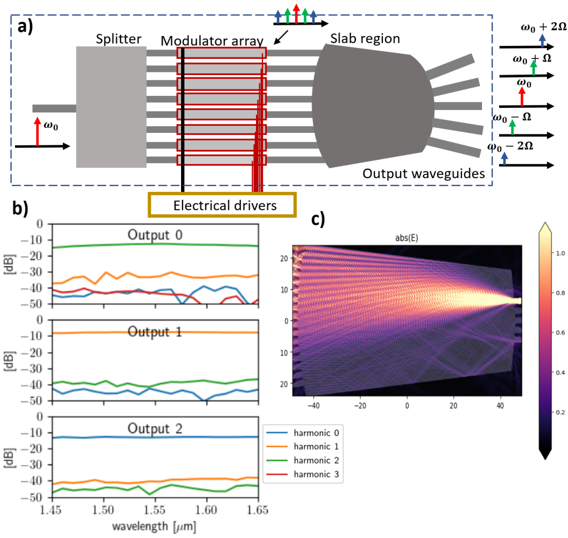

Fig. 2: a) Schematic of a multi-beam frequency shifter. b) Simulated performance combining s-parameters and harmonic content under perfect phase modulation (modulation depth 1.84, phase delay between modulators 1.25 radians). Outputs 0 to 2 are shown; others are symmetric for negative hamronics. c) 2D FDTD simulation of the star coupler for calculating s-parameters related to output 0 (upper right output).

the LDV beams. This results in either 2 or 4 read-out pads per beam, depending on the photodetection readout method.

In contrast, Figure 3a illustrates a synthetic array architecture using the multibeam frequency shifter similar to the rainbow heterodyne free-space architectures [6]. Here, the measurement light is processed by the multibeam frequency shifter. The reference beam is frequency shifted by a single beam frequency shifter. The reflected measurement beams, combined with the frequency-shifted reference, are detected by photodetectors. Figure 3b shows the process in the optical and electrical frequency domains; the multibeam frequency shifter generates different harmonics (in red), and interference with the frequency-shifted reference (in green) results in signals downshifted and separated in the electrical frequency domain. While around 16 and 4 connections are necessary for driving the multibeam frequency shifter and the reference frequency shifter, only two electrical contacts are required to read out 5 beams. Considering 5 beams we can see that the number of electrical connections necessary for is similar for both architectures. This changes however when we increase the number of beams and take into account that we can connect additional on-chip frequency shifters in parallel, hereby sharing the electrical contacts from the chip. Scaling analysis in Figure 3c reveals that the multibeam frequency shifter architecture offers a more efficient solution in terms of electrical connections/pads. For example, when scaling to hundred beams, the former would need approximately 400 pads, while the latter would require only around 60. Additionally, the wavelength stability of the multibeam frequency shifter (as can be seen from Fig. 2b opens possibilities for sharing a single multi-beam frequency shifter among various wavelengths.

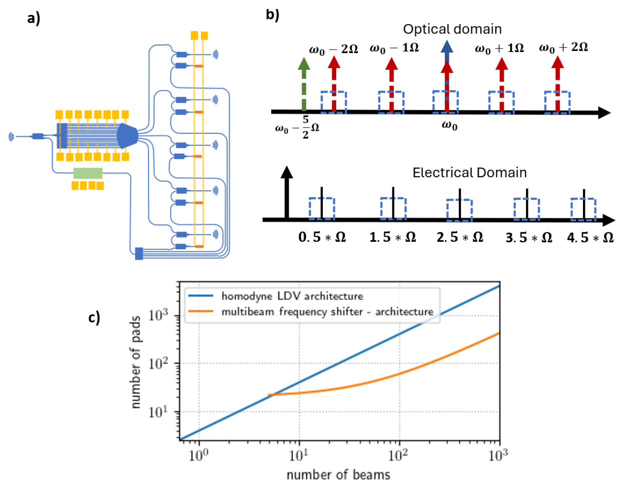

Fig. 3: a) multi-beam architecture using multibeam frequency shifter, and a single beam frequency shifter in green. b) Optical spectrum with the shifted reference (green) and measurement signals encoded in the blue region around the heterodynes in red. Combining the reference and measurement signals on a photodetector results in an electrical spectrum where the different signals are separated. c) Scaling analysis of different archtecture of the number of pads vs the number of beams

IV. CONCLUSION

In conclusion, using a multi-beam frequency shifter we introduced a scalable architecture for multibeam LDVs. Scaling analysis has shown that this approach substantially increases the number of beams, overcoming the limitations posed by the amount of electrical connections compared to homodyne LDV layouts, enabling the deployment of LDVs with high beam counts.

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