# Single-photon Calibration of an Integrated Multiarm Interferometer via Neural Netowrks

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**Abstract:** Technological quantum sensors requires the development of a calibration procedure that is self-consistent and easily adaptable to different scenarios. Neural networks provide a handy solution in particular when dealing with large systems operating in a noisy environment.

The study of the properties of a physical system: from the identification of its state through state tomography, to the description of the system's dynamic evolution using process tomography, can be a really difficult data analysis task for large systems in noisy environments. This is also the case for the characterization of quantum sensors in particular for those whose operation depends on multiple parameters [1]. Their operation characterization through tomography is in general a resource and computational expensive procedure, requiring the capability of generating different classes of input states. Besides the complexity of the approach, this may not be in general a viable option from the point of view of an end user, since the architecture of the quantum sensors may not permit to generate the necessary states for such complete characterization. In this scenarios the use of machine learning and more specifically of neural networks (NN) can become particularly helpful [3]. To obtain an accurate description of the device functioning, NNs do not need an analytic model of the system, since they just need inputs and outputs data for the training, and thanks to their universal applicability, they can be used to approximate with high accuracy any complex continuous function.

Integrated photonics represents a benchmark platform to study multiparameter estimation problems thanks to the ability of implementing complex circuits with reconfiguration capabilities [2]. Here, we demonstrate the calibration at the single-photon level of a multiphase sensor consisting in an integrated three-arm interferometer realized by the femtosecond-laser-writing technique [4]. The internal phases of the multi-arm interferometer can be tuned applying different voltages to the Ohmic resistors embedded into the integrated device. The application of a pair of voltages $(V_1, V_2)$ generates a different global phase shift along each optical path, resulting in a different action of the device (Fig.**a**)).

The chip functioning can be studied sending single photons in one of its three input ports and collecting the photon counts at the three outputs of the device. In this way, single-photon probabilities $P(i \to j)$ for each output $j$ $(j = 1,2,3)$ are measured by changing the input arm $i$ of the single-photon state and tuning the power dissipated on the internal resistors. To avoid the need of developing a full model of the internal operation of the sensor, which should in principle take into account the different sources of noise and cross-talk between the multiple parameters tailored to the specific device, we employ a NN algorithm to perform the mapping between voltages and output probabilities (Fig. **b)-c)**).

The network has been trained associating the applied controlled voltages $V_1$ and $V_2$ to the 6 corresponding input-output probabilities obtained when injecting a photon respectively in the first and second input of the device. Due to the non-injectivity of the output probabilities, resulting in the presence of multiple parameter points that correspond to the same probability values, it was necessary to provide to the network additional information about the probability functions. In particular, we incorporate into each training example the further set of probabilities $\tilde{P}(i \to j)$ corresponding to the probability values obtained by changing the two voltages of a fixed value.

The training was performed with the results obtained after the application of 53 different tensions values to each of the two resistors in the device. This gives a tension grid with $53 \times 53 = 2809$ different tension pairs associated to the relative input-output probabilities available to train the network.

In order to study the NN performances we compute the normalized root mean squared error (NRMSE) at each training epoch. Once established the network architecture achieving the best performances, we investigate how the NRMSE on an independent set of data i.e. the validation set changes reducing the number of tension pairs used for the training. This choice is performed to assess how much reducing the data for the training affects the final network estimation of new examples. The results are shown in Fig.( **d**)). As expected, the NRMSE achieved by the network decreases as the number of training examples increases, allowing a better reconstruction of the function, mapping the input vector onto the output one.

The use of NNs for the calibration of quantum sensors, allows to overcome the problem of developing a detailed theoretical model encompassing all sensor parameters, their cross-talk and the effect of noise, otherwise crucial to perform an accurate interpolation procedure. The reconstruction of the device functioning in general is not a trivial problem and it gets more and more complicated as the number of parameters on which the device response function depends on increases. For this reason their calibration through machine learning based techniques becomes extremely useful in the perspective of large scale fabrication of multiparameter quantum sensors.

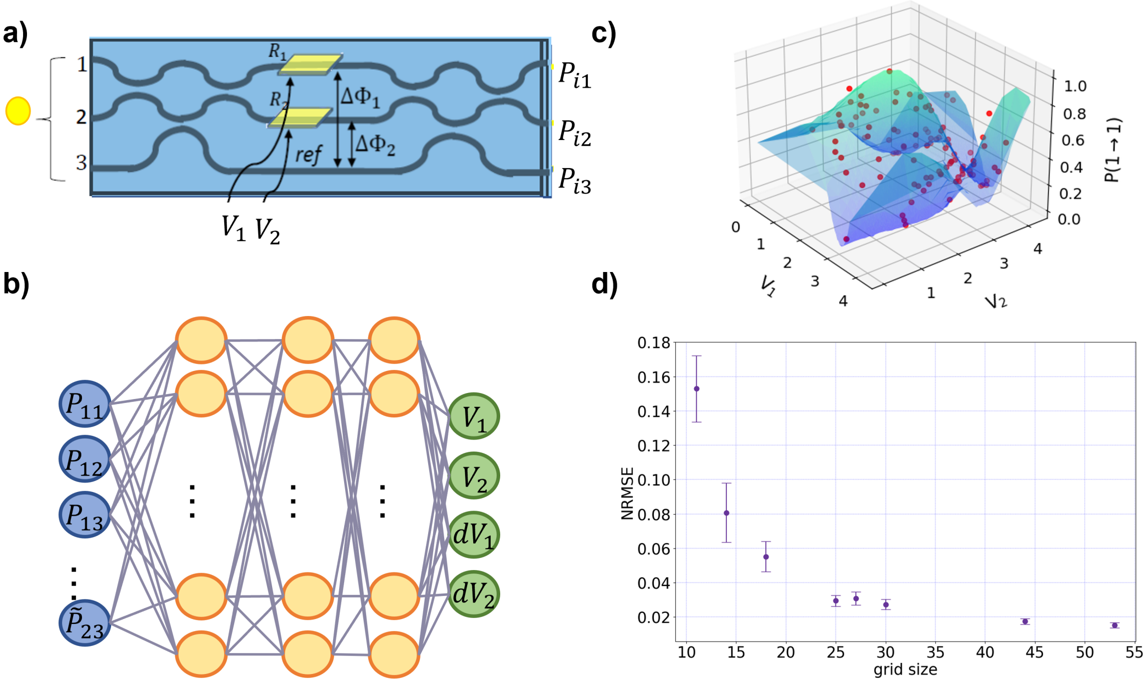

Fig. 1. **a)** Scheme of the integrated circuit: Single photons are injected in the inputs of the three-arm interferometer and detected by avalanche photodiodes. The output probabilities $P_{ij}$ can be reconstructed as function of the applied voltages $V_1$ and $V_2$ controlling the internal optical phase-shift among the interferometer arms. **b)** Architecture of the feed-forward neural network employed for the calibration. **c)** Example of one of the input-output probabilities of the chip as a function of the applied voltages. The red dots show the results obtained with the trained NN while the blue surface represents the experimental measured results. **d)** NRMSE computed over the validation set for different amount of training data depending on the grid size

## References

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