Ultra-fast Phase Calibration for an Optical Phased Array

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Ultra-fast Phase Calibration for an Optical Phased Array

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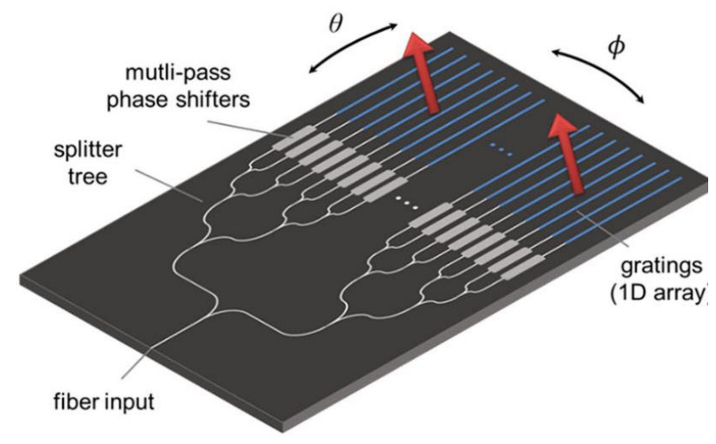
Abstract

An ultra-fast and novel phase calibration method for an optical phased array has been developed using the MODE API on Python. With an adaptive moment estimation (Adam) algorithm, the optimal phase set is obtained by finding the maximum light intensity in the target direction.

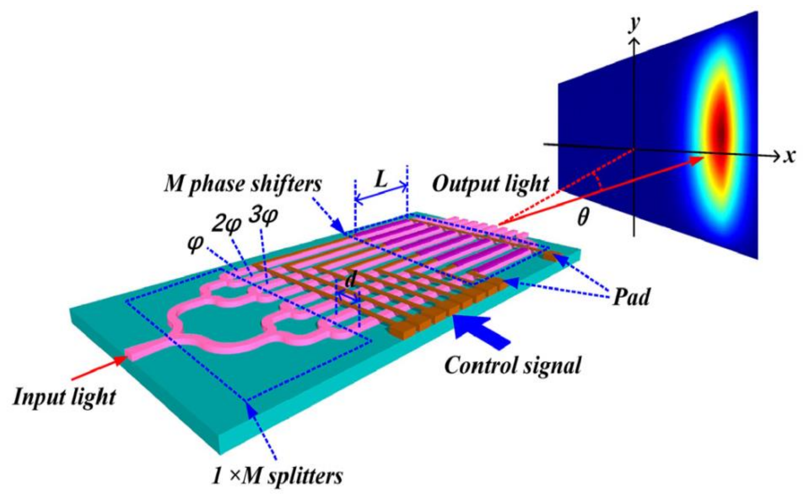
Introduction

✓ ***Optical Phased Arrays (OPAs)***

- Waveguides based OPAs have gained attraction due to a faster scanning speed and small form factor.



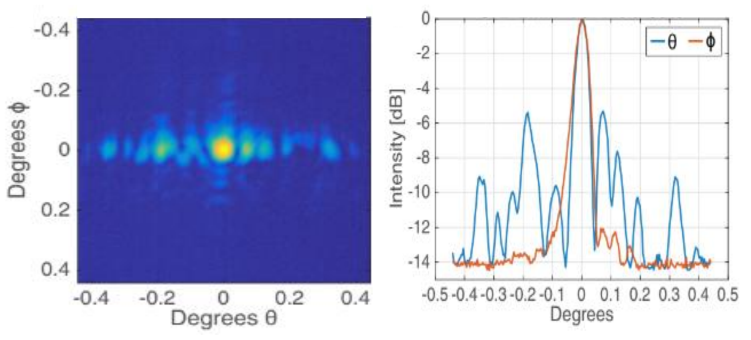
S.A. Miller et al., Optica, 7(1), 2020



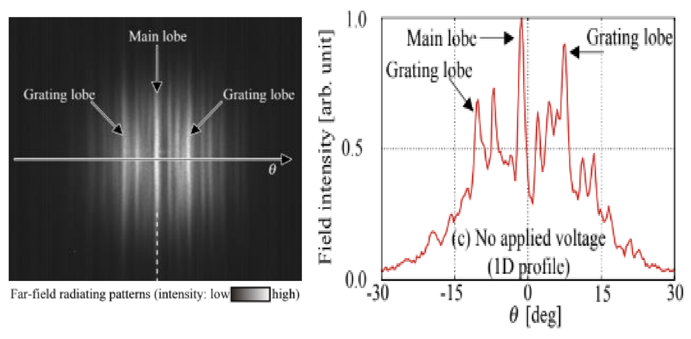
M. Tao et al., IEEE Trans Instrum Meas, 71, 2022

✓ ***Initial phase error***

- However, OPAs generally suffer from initial phase errors due to fabrication imperfection. These errors scatter the light power, producing a distorted farfield.



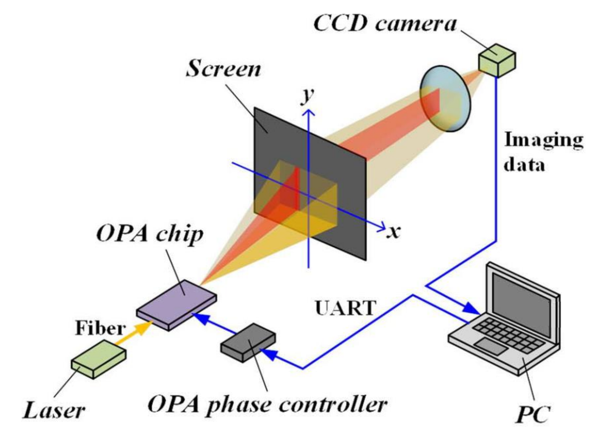
C.V. Poulton et al., MIT, M.S. dissertation, 2016



Y. Hirano et al., J. Appl. Phys. 57(3S2), 2018

✓ ***Calibration setup***

- Initial phase errors are unpredictable and random. Also, the relationship between relative phases among channels and the corresponding farfield is nonlinear.
- Therefore, it is practical to calibrate them using an iterative calibration algorithm with the farfield-feedback camera setup.



M. Tao et al., IEEE Trans Instrum Meas, 71, 2022

Algorithm	OPA channel #	Required iteration #	Reference
HC	16	100 (1.3 sec)	[1] J. K. Doylend et al., Opt. Express, 2011
HC	16	80	[2] G. Kang et al., IEEE Photon. Technol. Lett., 2019
DSGD	512	7048	[3] T. KOMLJENOVIC et al., Opt. Express, 2018
SPGD	32 8	20000 5000	[4] L. Li et al., IEEE Photonics J., 11(1), 2019
REV	1024 32	4096 16 second	[5] J. Jin et al., Opt. Express, 2022

Comparison table between different algorithm

✓ ***Limitations of conventional algorithms***

- However, some works reported the speed of calibration was limited by the frame rate of camera ([1],[5] in the comparison table.)
- Additionally conventional optimization algorithms such as genetic algorithm (GA), stochastic gradient descent (SGD), and Hill-climbing algorithm (HC) are not scalable and generally require a large number of iterations.
- Therefore, a calibration method with a low number of iterations is required.

Proposed method

✓ ***Proposed algorithm***

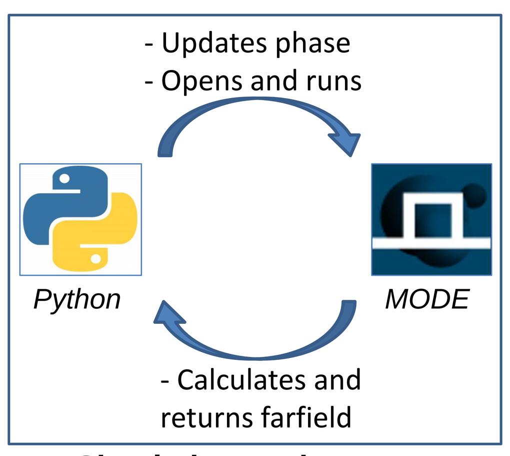
- **Adaptive Moment Estimation (Adam)** is a variant of gradient descent algorithm with 'velocity' and 'momentum.'
- It applies independent weights on every variable, and it determines the amount and direction of the changes by calculating the gradient of the loss function.
- As such, each variable changes independently and moves quickly to the optimal solution resulting in a low number of iterations.

Require: α: Stepsize
Require: $\beta_1, \beta_1 \in [0,1)$: Exponential decay rates for the moment estimates
Require: $f(\theta)$: Stochastic objective function with parameters θ
Require: θ_0: Initial parameter vector
  $m_0 \leftarrow 0$ (Initialize 1st moment vector)
  $v_0 \leftarrow 0$ (Initialize 2nd moment vector)
  $t \leftarrow 0$ (Initialize timestep)
  while θ_t not converged **do**
    $t \leftarrow t+1$
    $g_t \leftarrow \nabla_\theta \cdot f_t(\theta_{t-1})$ (Get gradients w.r.t. stochastic objective at timestep t)
    $m_t \leftarrow \beta_1 \cdot m_{t-1} + (1-\beta_1) \cdot g_t$ (Update biased first moment estimate)
    $v_t \leftarrow \beta_2 \cdot v_{t-1} + (1-\beta_2) \cdot g_t^2$ (Update biased second raw moment estimate)
    $\widehat{m}_t \leftarrow m_t/(1-\beta_1^t)$ (Compute bias-corrected first moment estimate)
    $\hat{v}_t \leftarrow v_t/(1-\beta_2^t)$ (Compute bias-corrected second raw moment estimate)
    $\alpha_t \leftarrow \alpha \cdot \sqrt{(1-\beta_2^t)}(1-\beta_1^t)$ (Compute bias-corrected stepsize)
    $\theta_t \leftarrow \theta_{t-1} - \alpha_t \cdot m_t/(\sqrt{\hat{v}_t} + \hat{\epsilon})$ (Update parameters)
end while
RETURN θ_t (Resulting parameters)

Pseudo-code of Adam

✓ ***Simulation method***

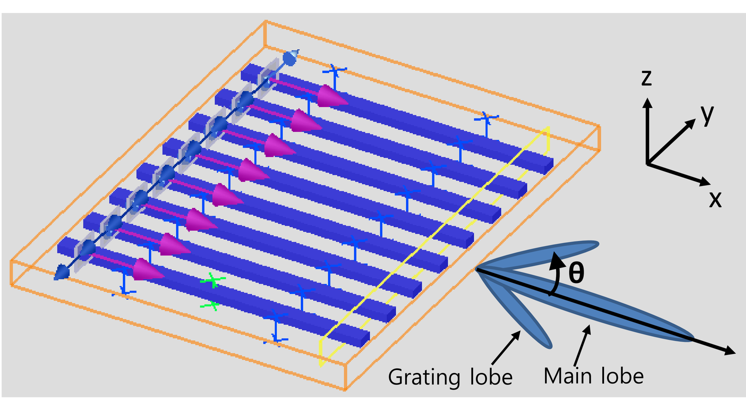
- In order to simulate the phase calibration using Adam, we utilized the variational finite-difference time-domain (varFDTD) tool in **MODE** (Ansys Lumerical Inc.), and we automated it **using its API on Python**.
- We took an one-dimensional periodic Silicon-Nitride waveguide array as the OPA model with the parameters presented below.



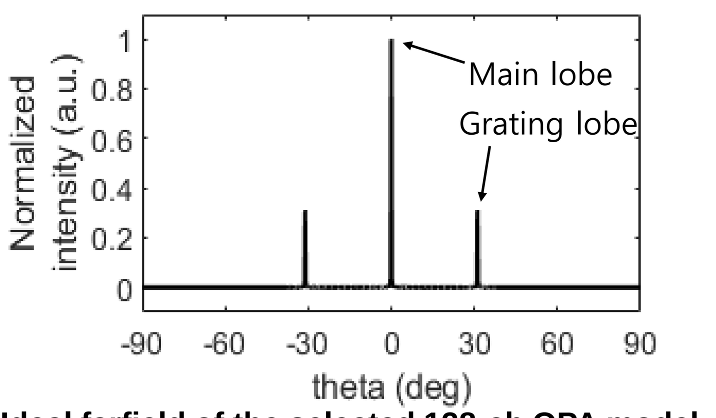
Simulation environment

Symbol	Value	Unit	Description
N	32, 64, 128	-	The number of channels
λ	1.55	um	Wavelength
l	20	um	Length of waveguides
w	1	um	Width of waveguides
t	0.5	um	Thickness of waveguides
d	3	um	Channel spacing
n_{SiN}	1.97	-	Refractive index of core (SiN)
n_{SiO2}	1.44	-	Refractive index of clad (SiO2)
n_{air}	1	-	Refractive index of farfield material(air)

Parameters of the selected OPA model



An example image of the selected OPA model



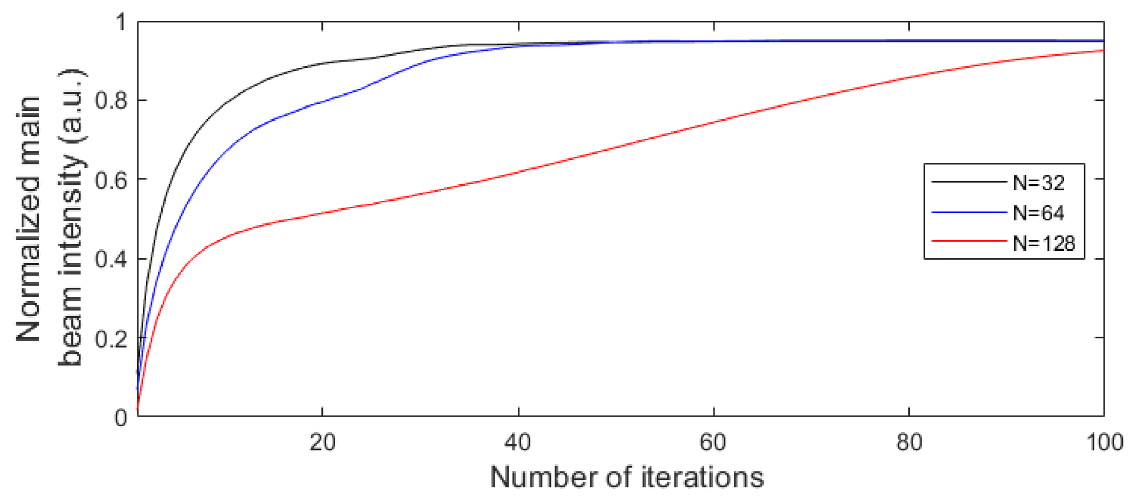
Ideal farfield of the selected 128-ch OPA model

- Initial phase errors are given by the uniform random distribution, covering one phase cycle (0, 2π).
- The loss function is the reciprocal of the intensity of one main lobe and two side lobes with weighted by 1 and 0.5 respectively

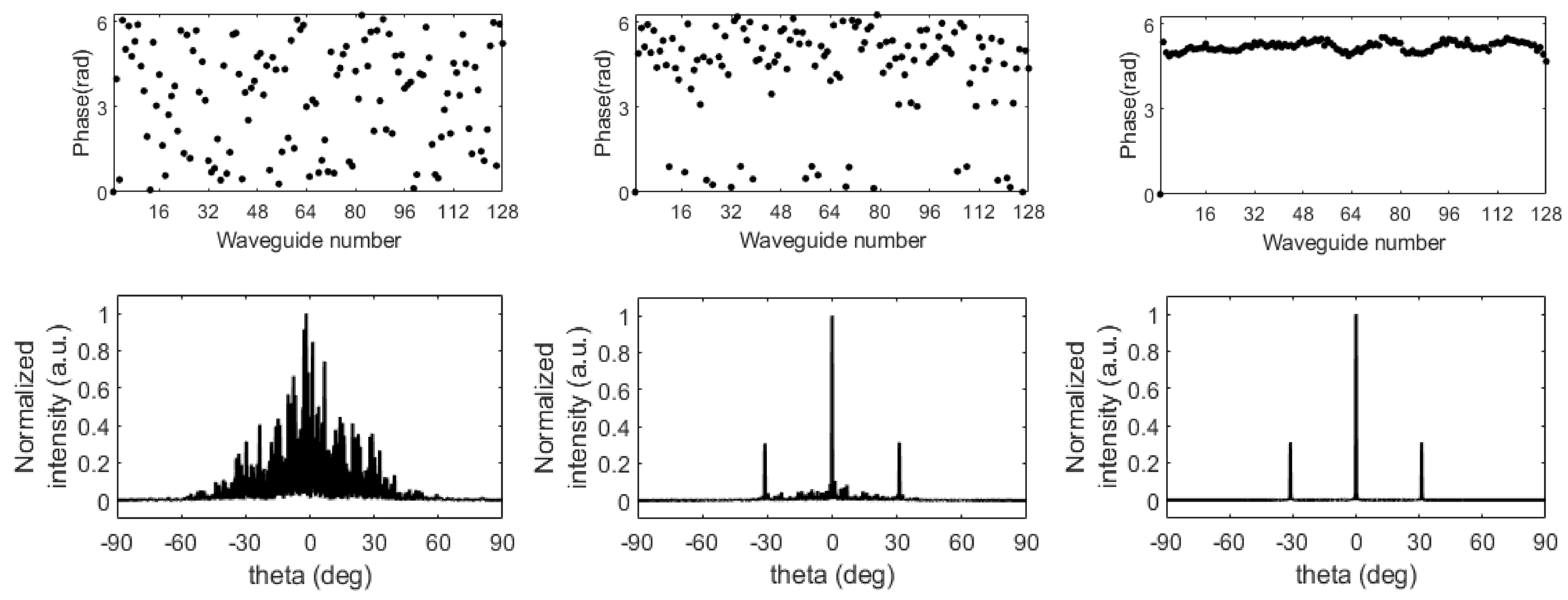
Simulation result

✓ ***Results***

- Only after 100 times of iterations the main beam intensity reached over 92% of the ideal case which has no phase errors regardless of the number of waveguides, going through numerous local extremum.



The normalized main beam intensity respect to the number of iterations (intensity 1 means the ideal intensity without initial phase errors)



(a) (b) (c)

The phase distribution and its corresponding farfield of the 128-ch OPA: (a) in the initial state, (b) after 10 times of iterations, (c) after 100 times of iterations

Conclusion

- An ultra-fast phase calibration method is developed using the MODE API on Python.
- Adam converged within 100 times of iterations, showing that it is promising to be utilized as phase calibration algorithm for OPA in the future.

Acknowledgement

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