A picosecond pulse array synthesizer for precise quantum control of atomic dipoles

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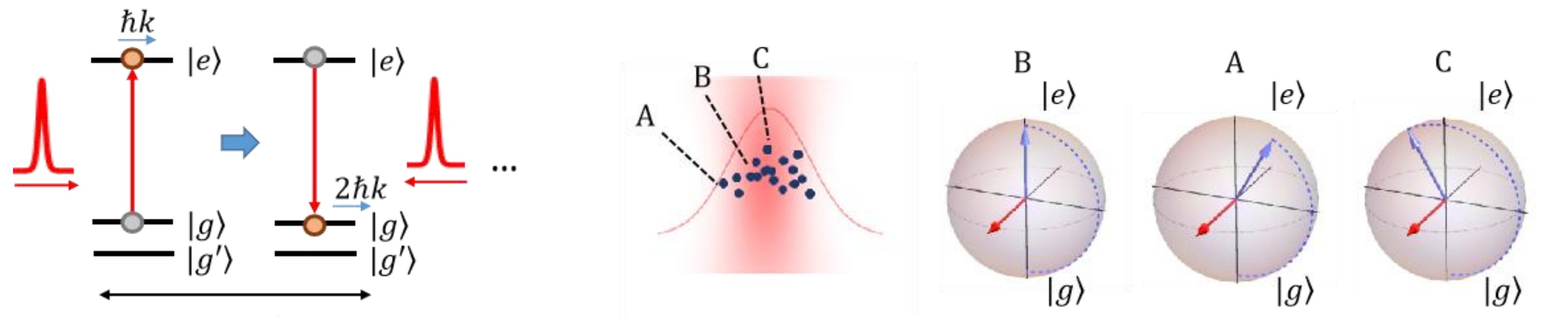
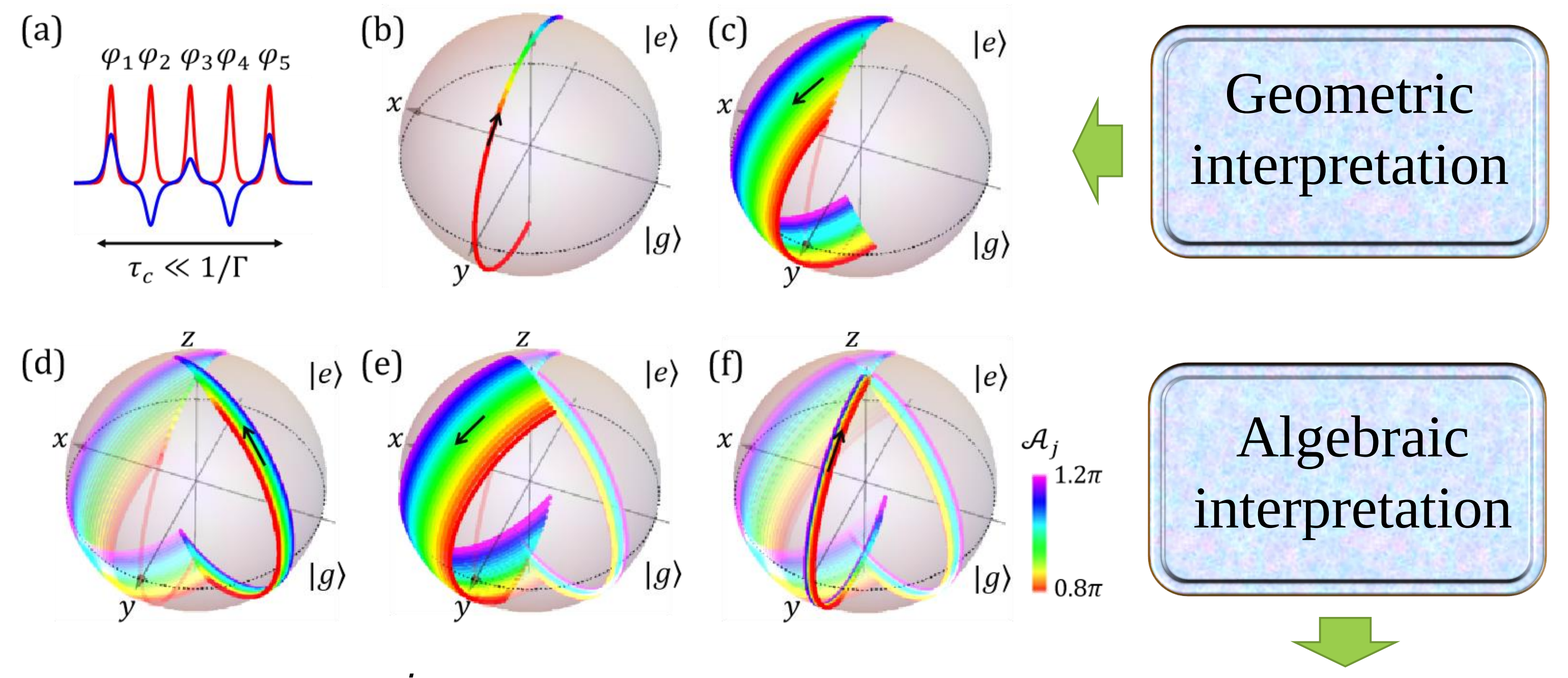
Introduction

Motivation: From laser cooling to atom interferometry, precise control of matterwave relies on transfer of photon recoil momentum to atoms. Conventional optical force relies on absorption and spontaneous emission cycles, which is not only with limited strength, but also prone to dark state trapping. Optical force based on stimulated emission can overcome the limitations, with potential applications ranging from molecular laser cooling to ion-based quantum information processing. The main difficulty associated with generating precise stimulated force is precise atomic state control: To transfer $2N$ recoil photons to atoms with "fidelity" f requires single operation fidelity $f_1 \sim 1-(1-f)^N$, a formidable task in presence of intensity inhomogeneity and spontaneous emission.



Composite picosecond control: For laser pulses with picosecond τ_c and sub-THz bandwidth, optical transitions are well-approximated by coherent 2-level dynamics, thereby supporting ensemble control techniques, originally developed in Nuclear Magnetic Resonance (NMR) [1,2].



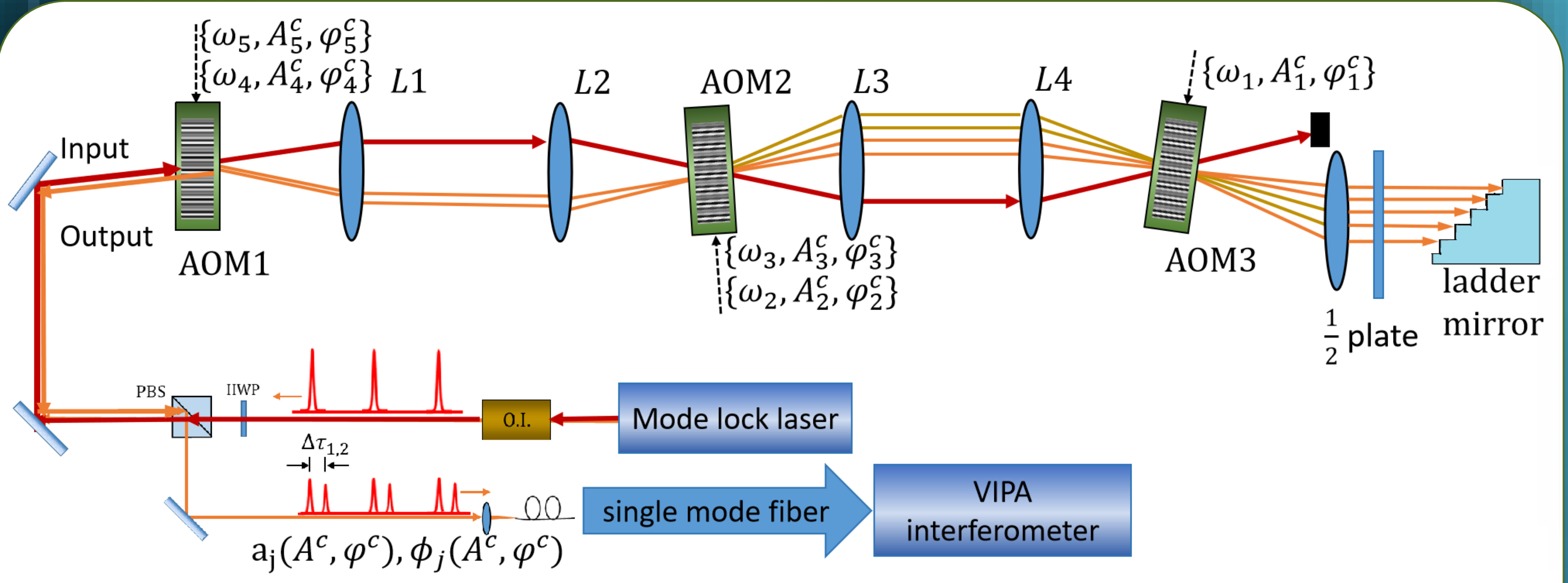
Geometric interpretation

Algebraic interpretation

$$\hat{U}_1(\mathcal{A}_1,\varphi_1)=e^{-\frac{i}{\hbar}\int_0^{\tau_1}\hat{H}(t)dt}\rightarrow \hat{U}^{(N)}(\epsilon_a)=\mathcal{T}\Pi_{j=1}^{N}\hat{U}_j(\mathcal{A}_j(1+\epsilon_a),\varphi_j)$$

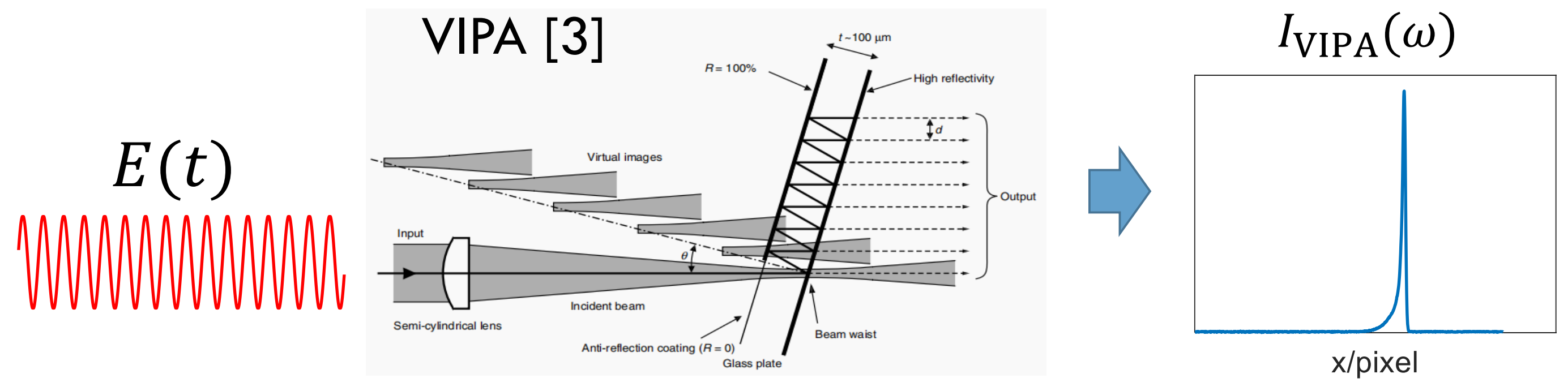
$$f=\left|\langle g|\hat{U}_{tar}^{\dagger}\hat{U}^{(N)}(\epsilon_a)|g\rangle\right|^2=\left|\hat{U}_{12}^{(N)}(\epsilon_a)\right|^2=1-\underbrace{\sum_{k=1}^{\infty}\alpha_k(\{a_j,\varphi_j\})\epsilon_a^{2k}}_{\text{Can be minimized}}$$

Pico-array generation



Direct Reciprocal-Space-to-Time pulse shaping

- We develop a composite-AOM based linear filter scheme to obtain picosecond pulse array with programmable amplitude and phase.
- Rf parameter $\{A_j^c, \varphi_j^c\}$ to pulse parameter $\{a_j, \varphi_j\}$ mapping



Acknowledgement & Reference

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[2] GENOV G T, SCHRAFT D, HALFMANN T, et al. Physical Review Letters, 2014, 113:043001.
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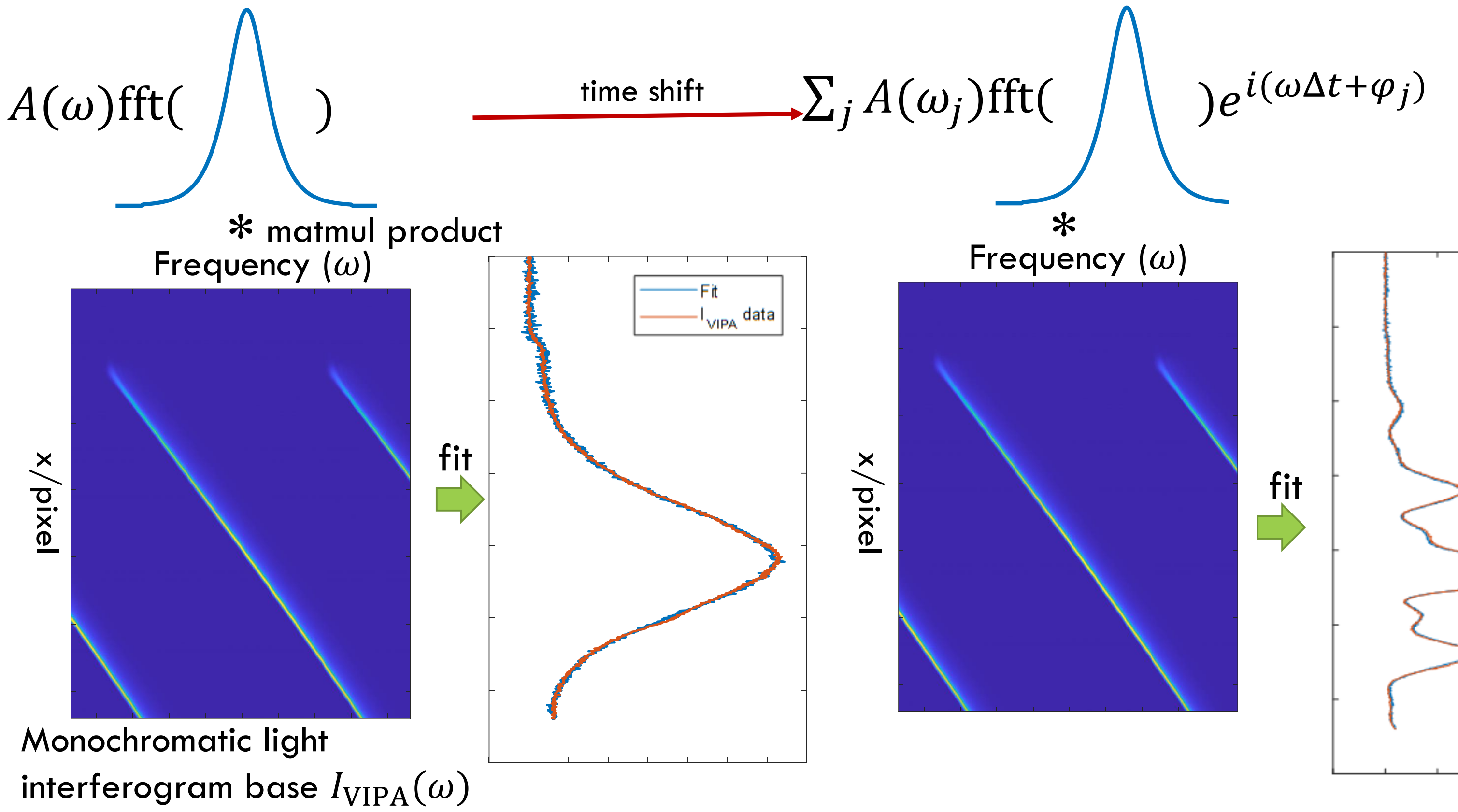
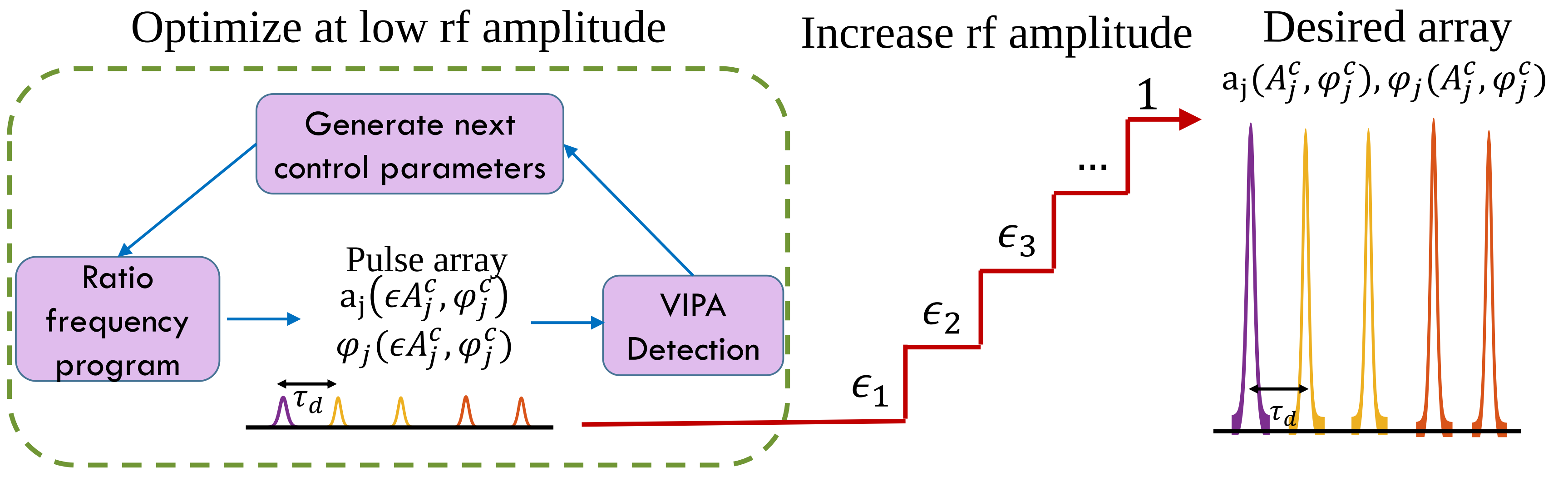
VIPA-characterization of pulse array



- We use pre-recorded monochromatic VIPA interferogram to decompose pulse-array spectrum.
- Parameter of single pulse is fit to $A(\omega)\mathrm{fft}\left(\mathrm{sech}\left(\frac{t}{\tau}\right)\right)$, with slowly varying $A(\omega)$, according to VIPA spectrum
- For pulse array, we fit $\sum_j C_j\ A(\omega)\mathrm{fft}\left(\mathrm{sech}\left(\frac{t}{\tau}\right)\right)e^{i(\omega\Delta t+\varphi_j)}$.

Pulse array parameter optimization

Practically, the acoustic wave parameters $\{A_j^c, \varphi_j^c\}$ to optical pulse parameters $\{a_j, \varphi_j\}$ mapping is nonlinear and can be quite complex. We develop a gradient-based optimization algorithm to produce the desired pulse array.



Optimization scheme

- We optimize the waveform parameters $a_j(\epsilon A_j^c, \varphi_j^c)$, $\varphi_j(\epsilon A_j^c, \varphi_j^c)$ with ϵ gradually increased from small enough value to unity.
- At each ϵ step, VIPA-retrieved $\{a_j, \varphi_j\}$ is compared to and optimized toward the target values, by adjusting the rf-parameters $\{\epsilon A_j^c, \varphi_j^c\}$.
- The optimization is straightforward in the linear regime with small enough ϵ.
- The optimal $\{\epsilon A_j^c, \varphi_j^c\}$ is transferred to the next round ϵ −step.

- Starting from $|a_j|^2 \sim 0.3\%$ we achieve $|a_j|^2 \sim 7\%$ AOM diffraction efficiency. The picosecond pulse array reaches a peak power of 10W.
- We estimate the pulse array parameters to be within ±10% in amplitude and ±0.05 radian in phase. The waveforms are stable, limited by M-L.

Summary and outlook

- We have developed a picosecond pulse array synthesizer that convert a mode-locked laser output into array of pulses with precisely programmable amplitude an phase. So far, the synthesizer operates reliably with up to $n=3$ sub-pulses. For $n \geq 3$ our optimization algorithm still meets some challenge to fully converge. Future efforts will focus on enhancing the optimization algorithm to accommodate longer pulse array shaping.

- Our pulse-array technique has the potential to bridge the technical gap for generating arbitrary shapeable optical waveforms with 10-100GHz bandwidth. The pulses can be highly useful for composite pulse control of strong optical transitions, to enhance the optical force to atoms and molecules with controlled stimulate emission, and for precise manipulation of collective spontaneous emission from cold atoms.

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