

# Acoustic-Optical Arbitrary Waveform Modulation for Raman atom interferometry



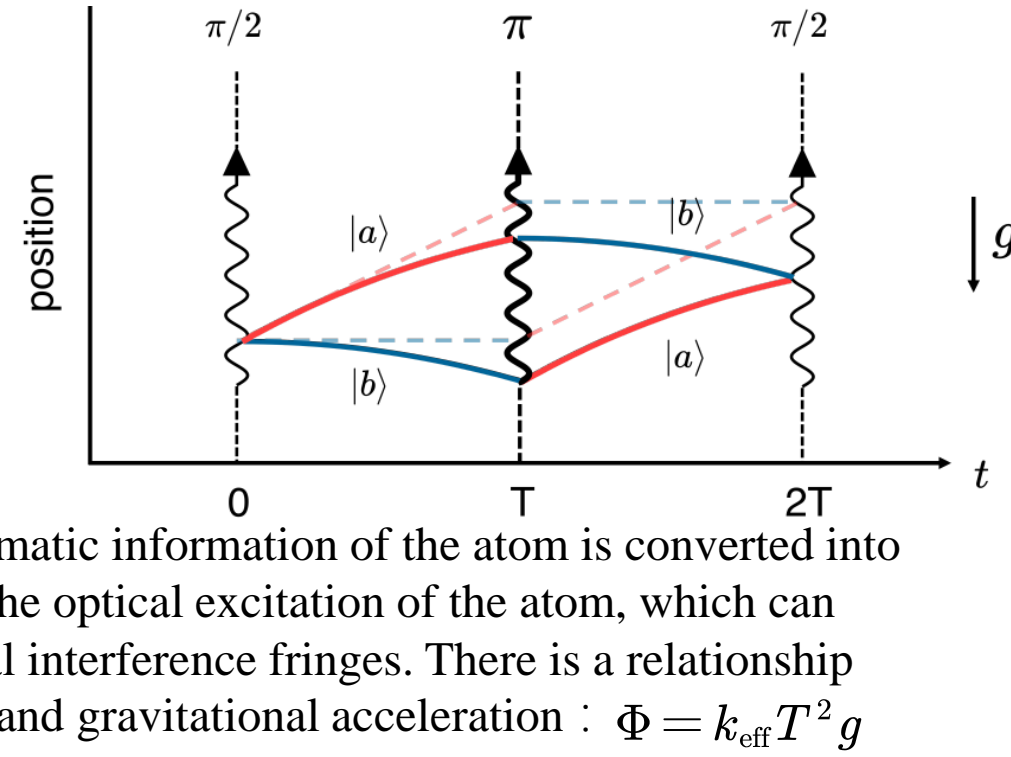
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## I. Research Motivation: Towards high-power arbitrary waveform Raman lasers

### A. Raman matter-wave manipulation and Raman interference

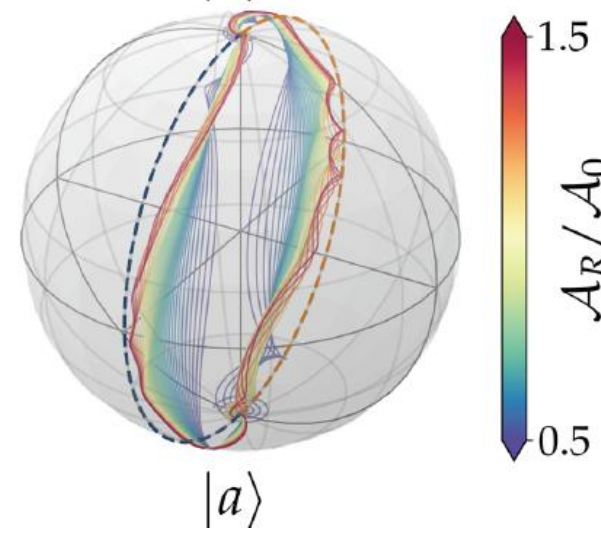
Atom interferometer: Achieves precision measurement of gravitational acceleration, gravity gradients, etc., through matter-wave interference. We adopted a Raman-manipulated Mach-Zehnder configuration.

As shown in the figure, atoms undergo a process splitting, reflecting, and recombining via  $\pi/2 - \pi - \pi/2$  quantum gate Raman pulses; the complex amplitudes of the same atom along two different paths to form interference, and the kinematic information of the atom is converted into the phase written during the optical excitation of the atom, which can then be read from the final interference fringes. There is a relationship between the fringe phase and gravitational acceleration:  $\Phi = k_{\text{eff}} T^2 g$



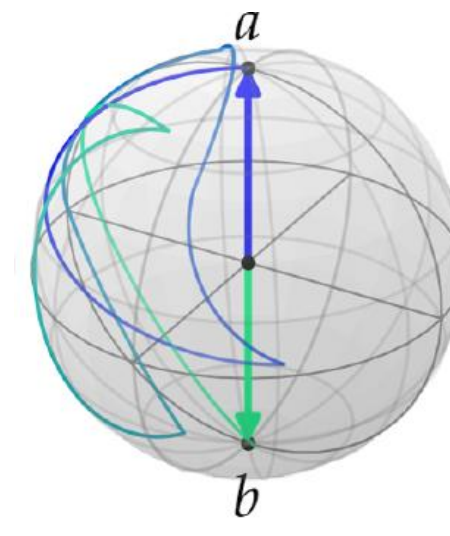
### B. Light intensity fault tolerance: Arbitrary waveform requirements

Adiabatic spin-dependent kick (SDK) pulses



Using rapid adiabatic passage pulses can flip the atomic spin and impart a two-photon recoil momentum. The manipulation of internal states by a pair of SDKs leaves only a geometric phase, exhibiting strong fault tolerance. In the atom interferometer, we use multiple sets of SDKs for acceleration during the atoms' free flight.

Composite pulse fault-tolerant quantum gates



Through the combination of multi-segment sub-pulses (equivalent to phase-modulated square waves), the phase degrees of freedom at each moment can be utilized to optimize quantum gate pulses that are fault-tolerant to parameters such as light intensity. In the atom interferometer, we use this to implement  $\pi$  and  $\pi/2$  gates.

### C. High-power laser requirements and the basic idea of this work

- High-power laser requirements: fEOM can withstand lower optical power  $\rightarrow$  limits spot size under the same light intensity  $\rightarrow$  limits atom cloud size  $\rightarrow$  limits atom free flight time (due to thermal motion diffusion)  $\rightarrow$  limits gravity measurement precision.
- Solution: Employing an Acousto-Optic Modulator (AOM).
- We studied the diffraction dynamics of the Acousto-Optic Modulator (AOM) and investigated the waveform modulation effects based on numerical simulations. Results: Simulations show that for square wave pulses, the main bottleneck of AOM modulation lies in the rising and falling edges as the acoustic field enters and exits the light spot; using an AOM with a higher operating frequency and reducing the spot size can significantly improve fidelity.
- For slowly varying waveforms, pulse waveforms with almost no distortion can be obtained through simple pre-correction of the acoustic field.
- Our preset ideal waveforms achieve over 99.9% fidelity in atom manipulation, while the pulses simulated by the AOM achieve over 99.5% fidelity.

## II. AOM Model and Raman-Nath Equations

Operating Principle: the plane-wave acoustic field within the crystal of an acousto-optic modulator (AOM) periodically alters the refractive index of the crystal, thereby inducing a thick grating effect that diffracts light incident at the Bragg angle.

The optical Schrödinger equation is given by:  $i \partial_z \psi = \left[ -\frac{1}{2k} \partial_x^2 + \frac{K}{2} [e^{i(k_x x + \varphi)} + c.c.] \right] \psi$ .

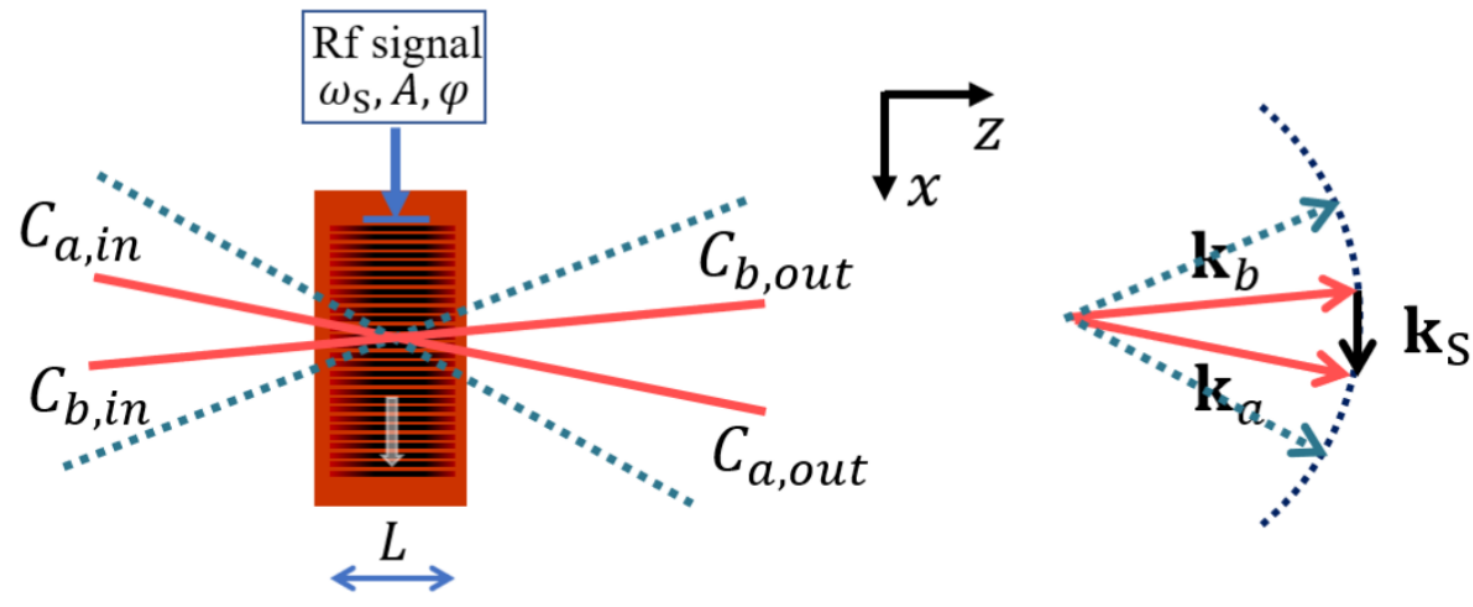
In reciprocal space, the coupling between different diffraction orders satisfies the Raman-Nath equation:

$$i \partial_z C_n(k_{\perp}, z) = \frac{[(n - \frac{1}{2})k_x + k_{\perp}]^2}{2k} C_n(k_{\perp}, z) - \frac{K}{2} e^{i\varphi} C_{n-1}(k_{\perp}, z) - \frac{K}{2} e^{-i\varphi} C_{n+1}(k_{\perp}, z).$$

The Hamiltonian under the two-level approximation is expressed as:

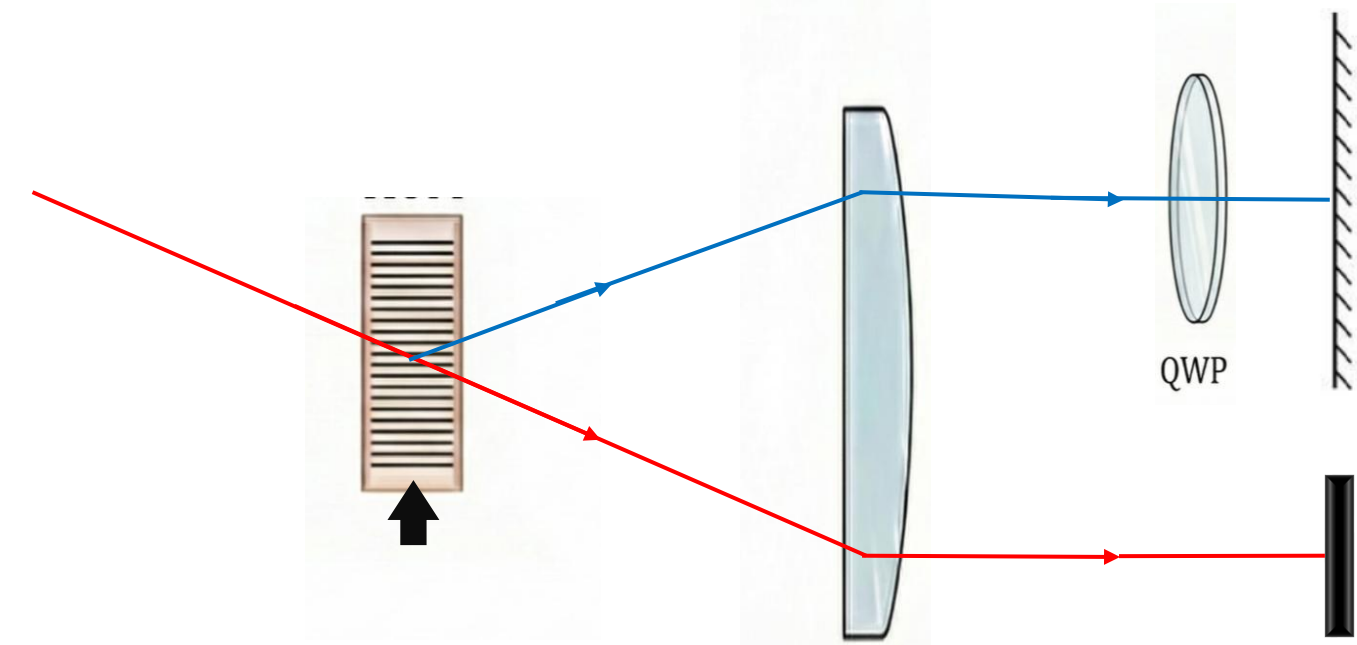
$$H(k_{\perp}) = \begin{pmatrix} \frac{(-\frac{k_x}{2} + k_{\perp})^2}{2k} & \frac{K}{2} e^{-i\varphi} \\ \frac{K}{2} e^{i\varphi} & \frac{(\frac{k_x}{2} + k_{\perp})^2}{2k} \end{pmatrix}$$

The first-order diffracted light acquires the phase of the acoustic field, while its wavefront retains a Gaussian-like mode.



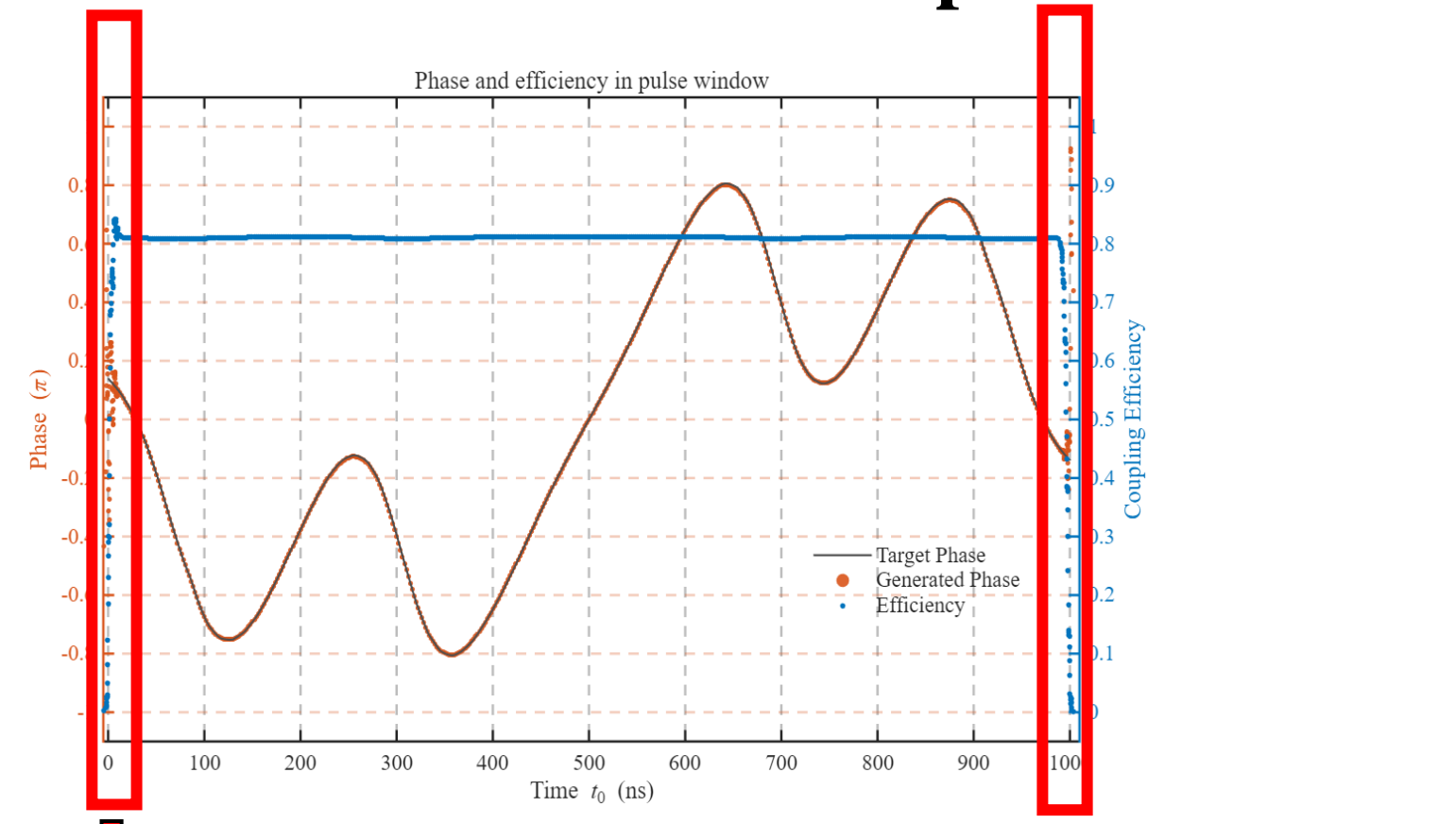
## III. Double-pass optical path

- Modulating pulses can be achieved by editing the amplitude and phase variations of the AOM's acoustic field waveform.
- Reason for double-pass: The double-pass configuration eliminates the change in the outgoing light path caused by frequency changes. Furthermore, the phase modulation amplitude of the acoustic field can be reduced by half, mitigating the lensing effect caused by an uneven acoustic field within the light spot.

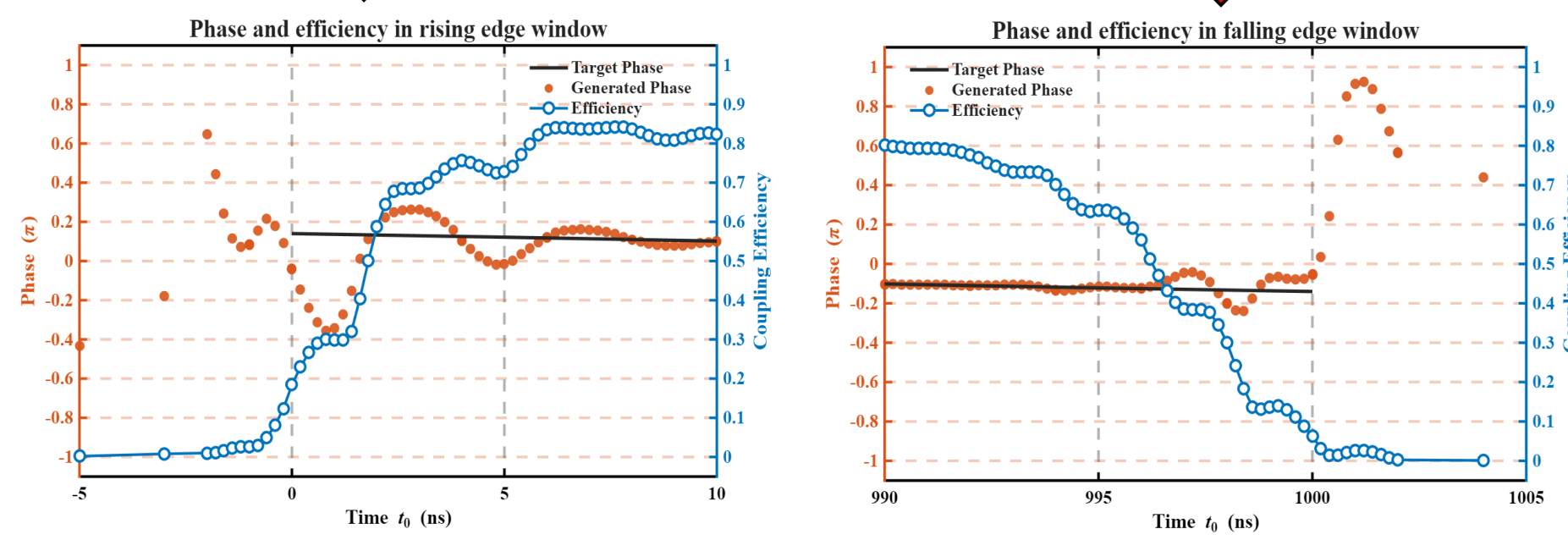


## IV. Arbitrary waveform modulation: Square wave phase modulation and step acoustic field transient response

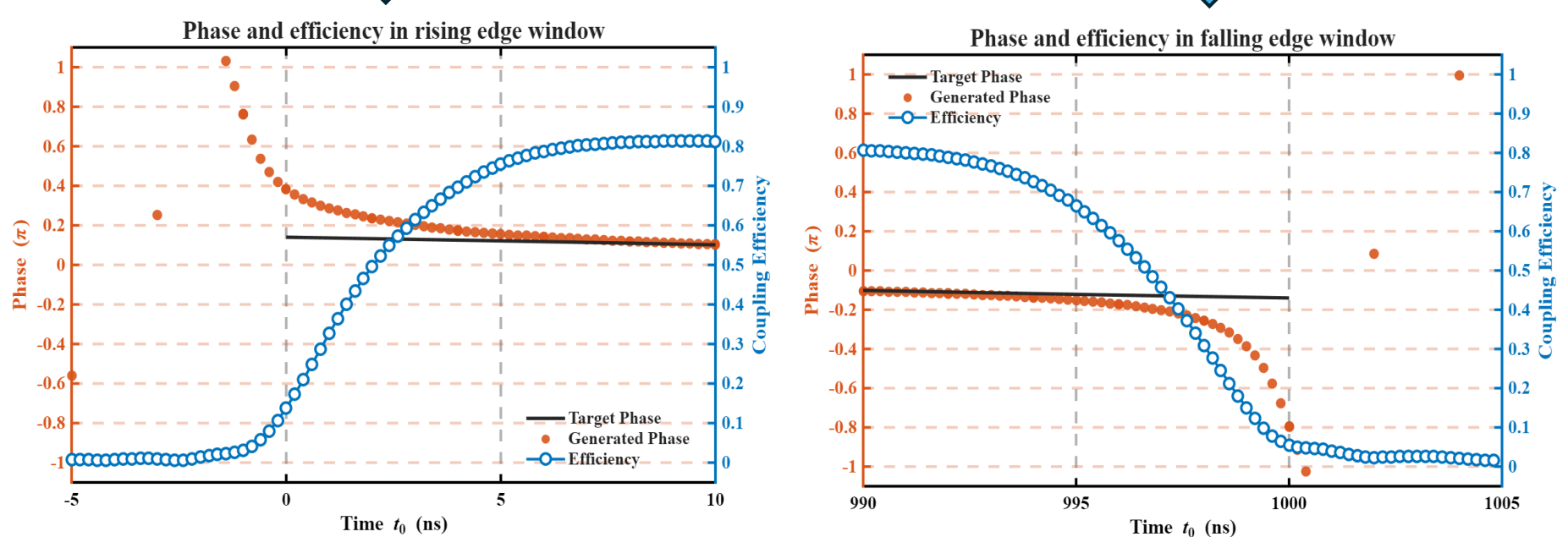
### A. Square wave phase modulation



### B. Transient response of intensity hopping:



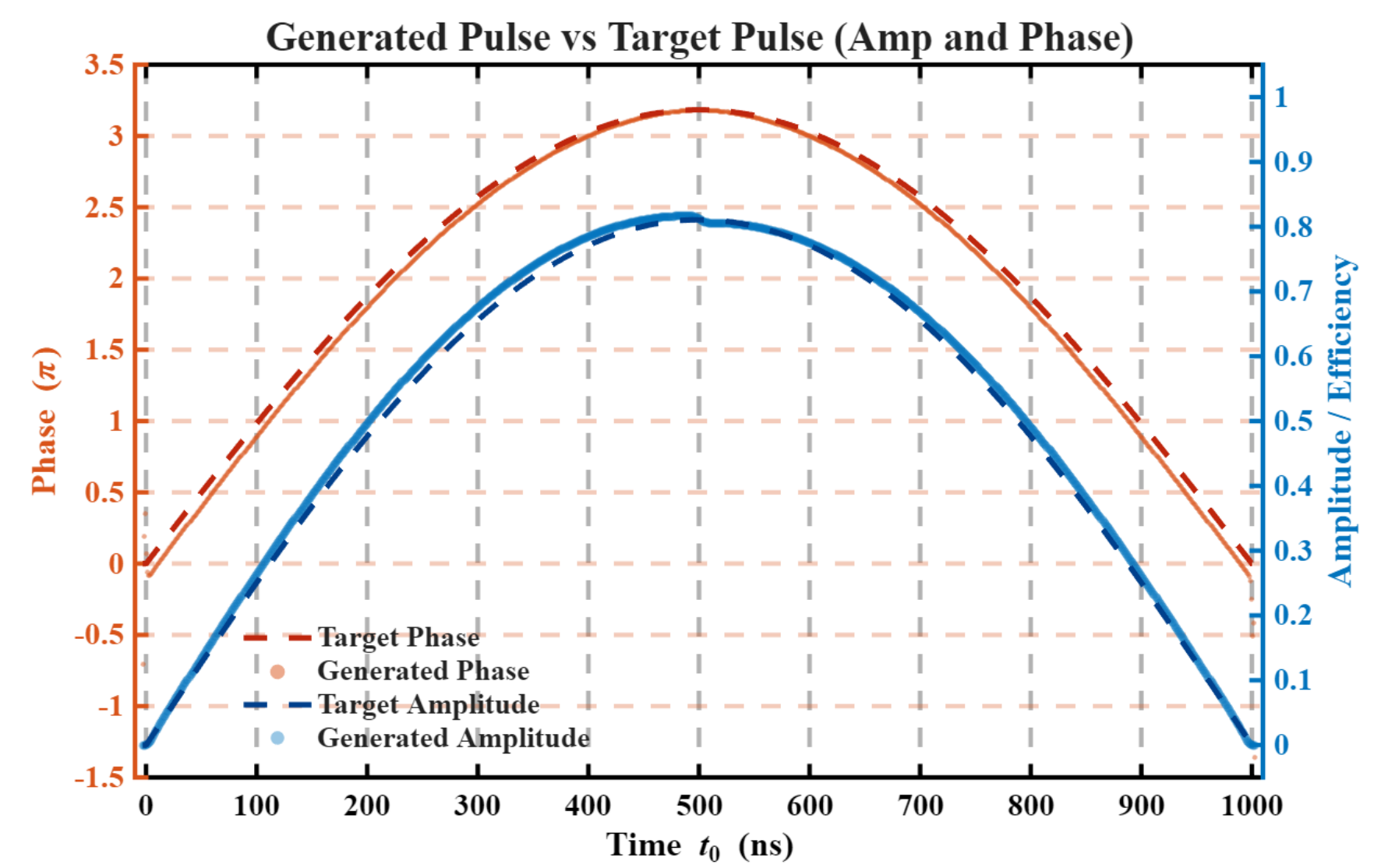
### C. Transient response of frequency hopping:



## V. Arbitrary waveform modulation: Sine SDK pulses

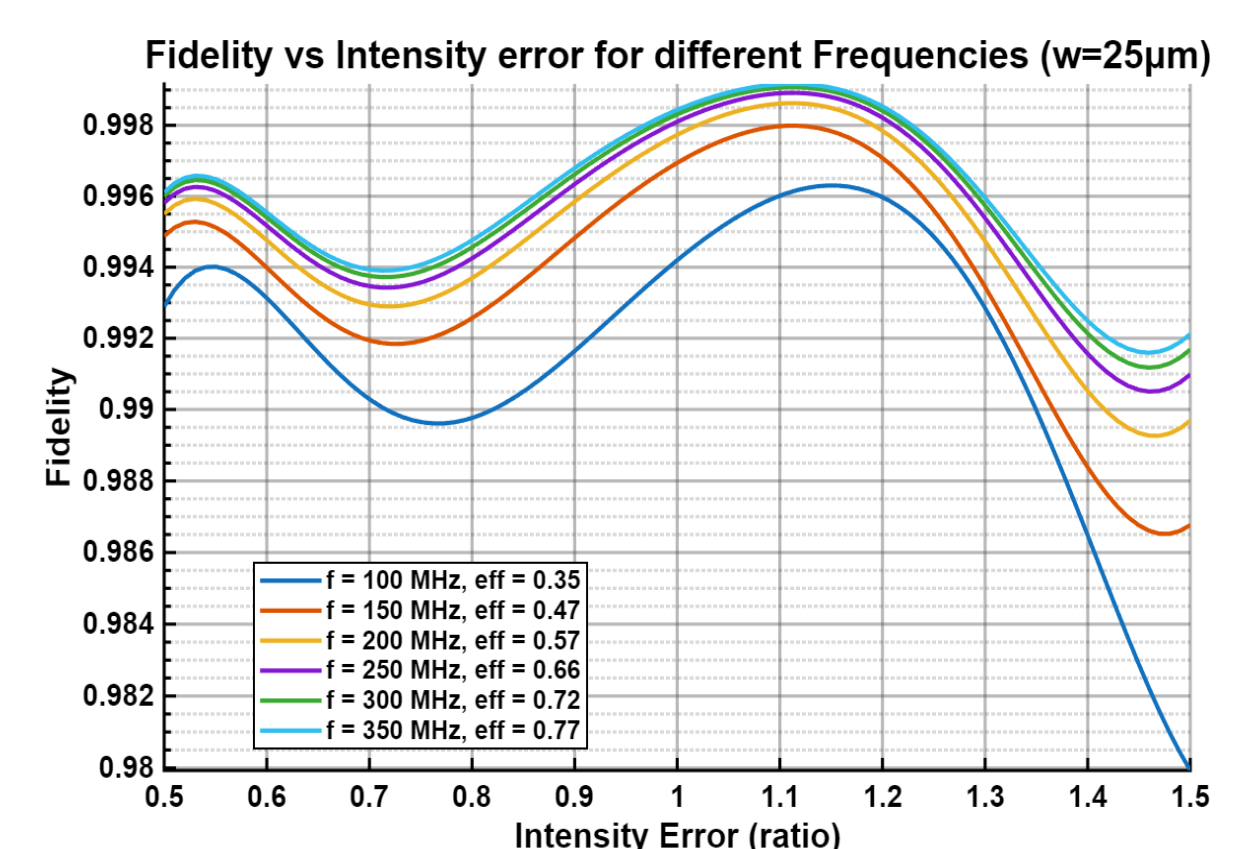
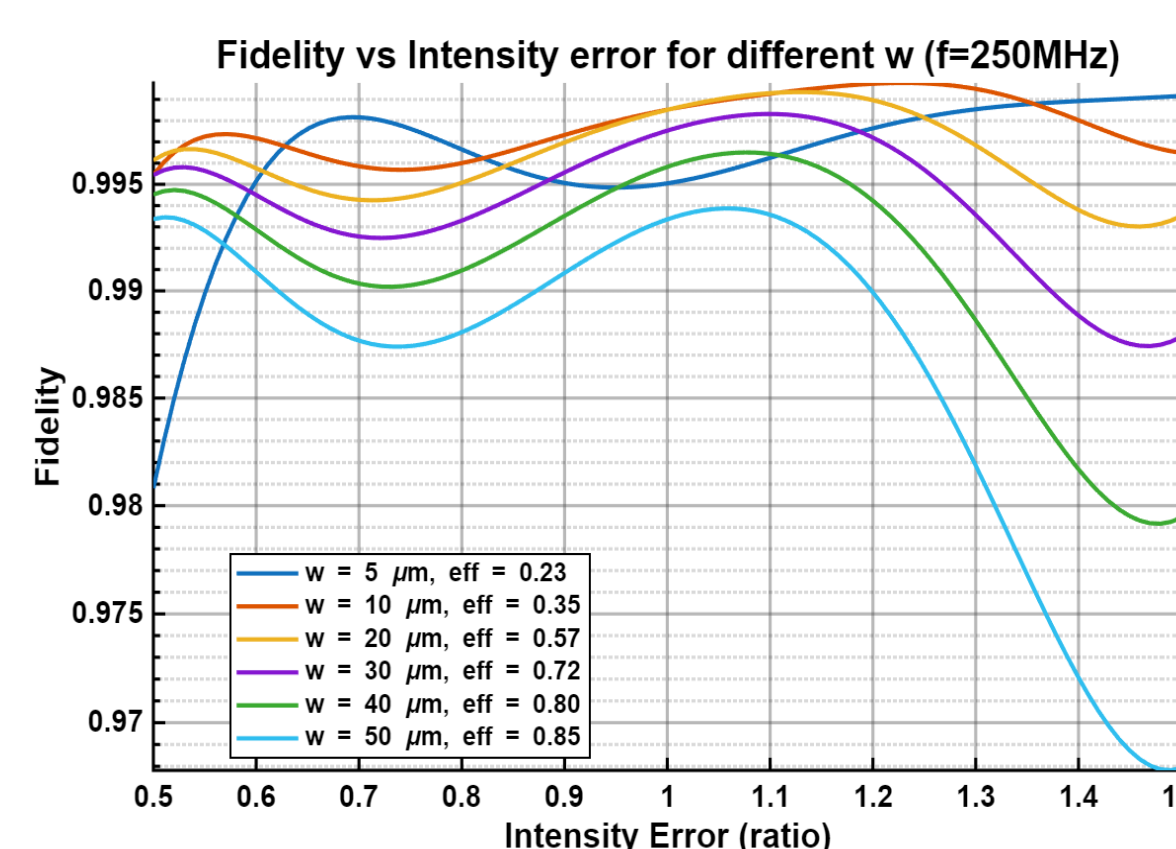
There is a non-linear relationship between the acoustic field waveform and the output pulse waveform. The acoustic field waveform correction formula for double-pass under the two-level approximation is:

$$f^*(t) = \frac{2}{\pi} \arcsin(\sqrt{f(t)})$$



## VI. Simulation Cases of Raman Response for Modulated Waveforms

- $\pi/2$  composite pulse quantum gate.
- Smaller spot observes a more uniform acoustic field.
- Increasing the operating frequency of the AOM can also improve fidelity and light intensity fault tolerance for decreasing the transverse movement length  $\theta_{\text{brag}} L_{\text{AOM}} \propto \frac{1}{f}$ .
- The study found that transverse movement may be related to the widely observed overshoot during AOM switching. When the spot is relatively small, after the transverse movement and misalignment of the 0th-order light with the 1st-order light, diffraction weakens or even backward diffraction occurs. Meanwhile, an acoustic field increasing along the moving direction of the 0th-order light precisely suppresses this effect.



## VII. Conclusion and Outlook

- Slowly varying waveforms, the AOM can modulate the target waveform without significant distortion.
- The step changes at the rising and falling edges of the square wave acoustic field will bring significant distortion and complex waveforms, but they can be greatly smoothed out via frequency hopping.
- The square wave quantum gates obtained from numerical simulations already have very high fidelity (>99.5%), and the main limitation lies in the rising and falling edges.
- Adopting a full-waveform smoothing approach can further improve fidelity.
- Employing our research group's CPAOM technology can further improve power utilization efficiency.