Composite Acousto-Optical Diffraction with Efficiency Exceeding 99%

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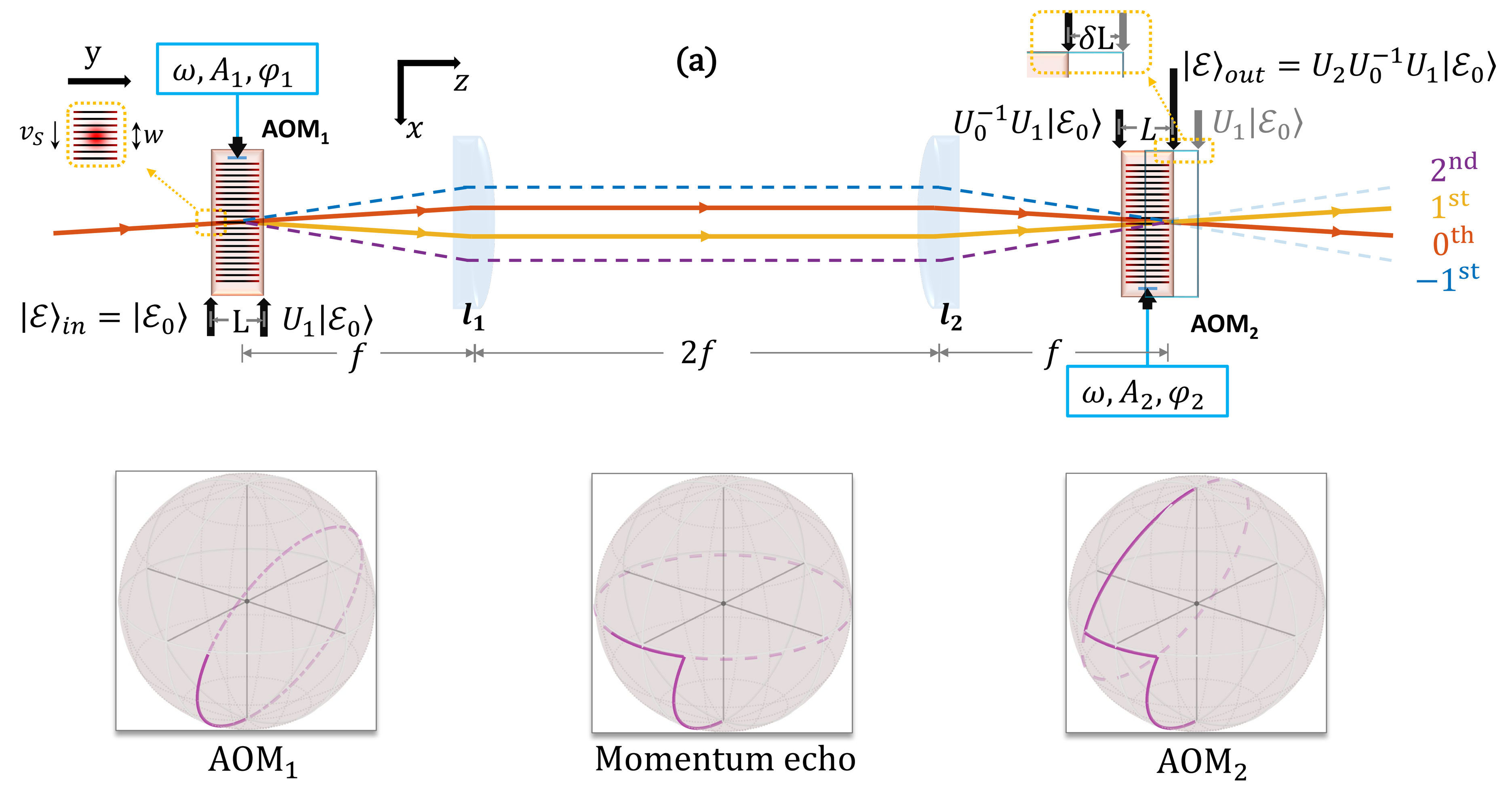
I. Introduction

Acousto-optical modulation (AOM) is a powerful, widely applied technique for rapidly controlling frequency, intensity and direction of light. Based on Bragg diffraction by sound, AOM is not known for its moderate diffraction efficiency, typically about 90% at best. In this work, we demonstrate beyond 99% efficiency in a composite-modulation (CPM) setup. The high efficiency 1st-order diffraction is accompanied by more than 30 dB single-mode suppression of the 0th-order beam. We discuss the underlying physics for the exceptional performance associated with optical rephasing. The two effects, referred to as "momentum echo" and "high-order rephasing" respectively, can be optimized almost simultaneously by tuning the relative distance between the two daughter-AOMs in the CP-AOM setup. We in addition demonstrate the highly efficient CP-AOM with a single AOM, using a Sagnac interferometer with a suitable round-trip optical delay. The exceptional performance enables CP-AOM as a high-contrast beam splitter with rapidly tunable splitting amplitude and phase. The device may find novel applications at the frontiers of laser physics and quantum optics.[1]



II. Modeling AOM interaction [2]

- **Paraxial equation**

$$i\partial_z \mathcal{E} = -\frac{1}{2\bar{n}k_0}\nabla_\perp^2 \mathcal{E} - \delta n k_0 \mathcal{E}$$

Moving index grating:
$\delta n = \eta\, p \cos(k_s x - \omega_s t + \varphi)$

Expansion under Bloch basis:
$\mathcal{E} = \sum C_m e^{i(\boldsymbol{k}_\perp + m\boldsymbol{k}_s)z}$

- **Raman-Nath equation**

$$i\partial_z C_m(\boldsymbol{k}_\perp, z) = \frac{\left[\boldsymbol{k}_\perp + \left(m - \frac{1}{2}\right)\boldsymbol{k}_s\right]^2}{2\bar{n}k_0} C_m(\boldsymbol{k}_\perp, z) - \frac{K}{2}e^{i\varphi}C_{m-1}(\boldsymbol{k}_\perp, z) - \frac{K}{2}e^{-i\varphi}C_{m+1}(\boldsymbol{k}_\perp, z)$$

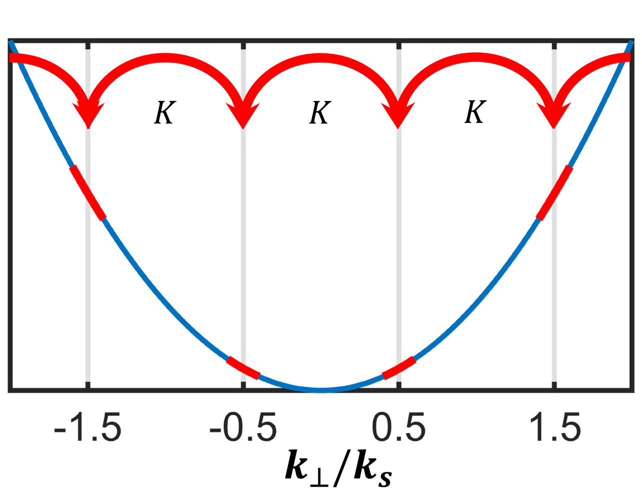
$K = \eta p k_0$

- **Hamiltonian**

$$H = \begin{pmatrix} \ddots & \ddots & & & & \\ \ddots & E_n & \Omega & & & \\ & \Omega^* & \ddots & \ddots & & \\ & & \ddots & E_1 & \Omega & \\ & & & \Omega^* & E_0 & \ddots \\ & & & & \ddots & \ddots & \Omega \\ & & & & & \Omega^* & E_{1-n} & \ddots \\ & & & & & & \ddots & \ddots \end{pmatrix}$$

"Energy shift":
$E_i = \frac{\left[\boldsymbol{k}_\perp + \left(i - \frac{1}{2}\right)\boldsymbol{k}_s\right]^2}{2\bar{n}k_0}$

"Rabi coupling":
$\Omega = -\frac{K}{2}e^{i\varphi}$



- Nearest order coupling

- **CP-AOM Propagator**

$$U = U_2 U_0^{-1} U_1$$

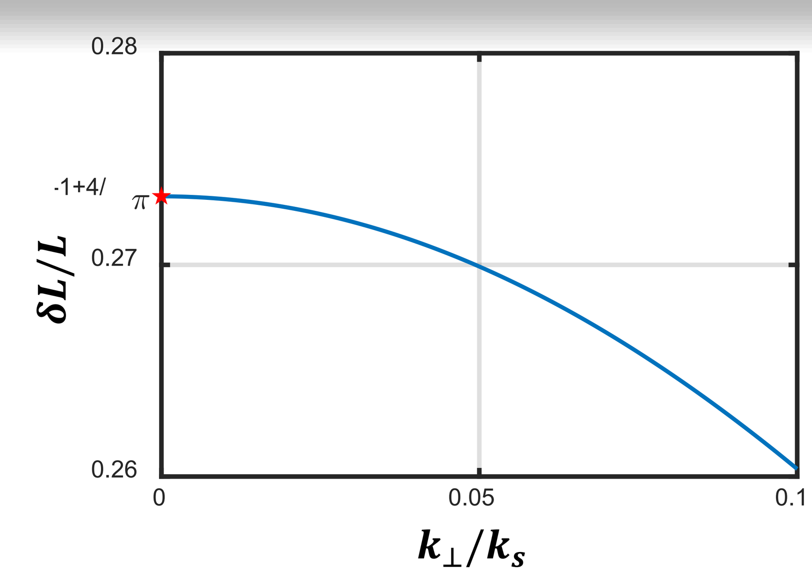
AOM$_1$: $U_1 = e^{-iH_1 L}$

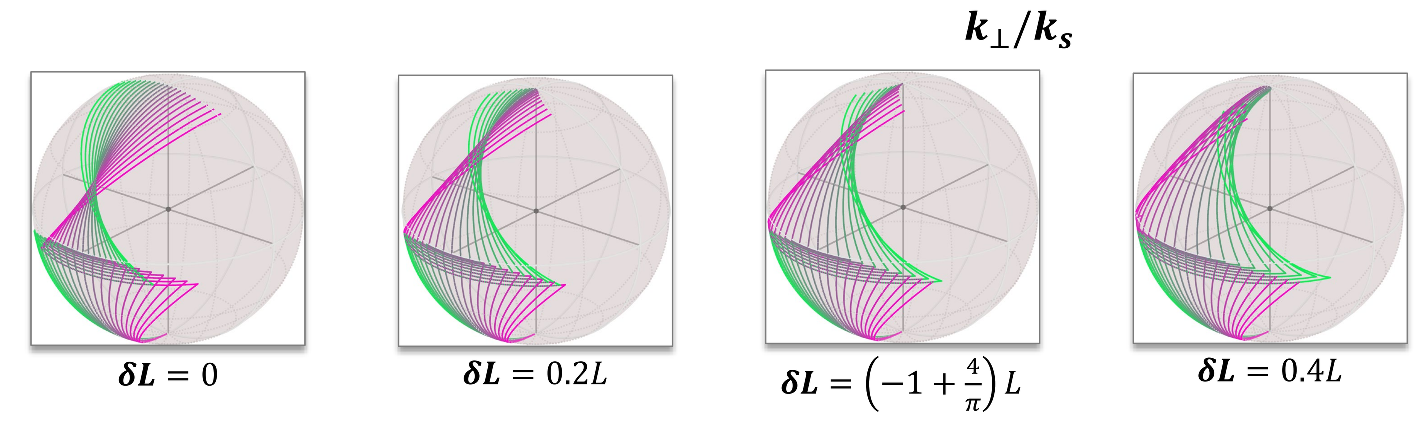
4-f imaging: $U_0^{-1} = e^{iH_0(L+\delta L)}$

AOM$_2$: $U_2 = e^{-iH_1 L}$

III. Momentum echo

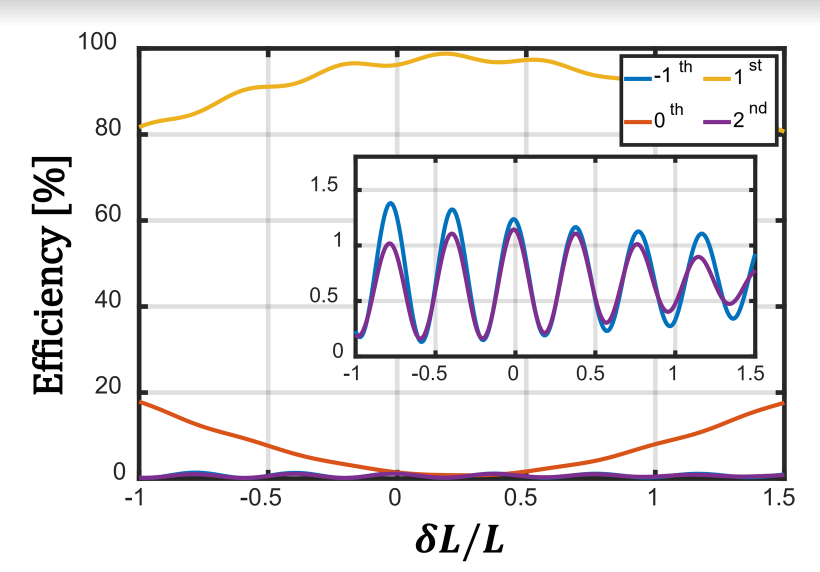
- Small relative displacement between AOM$_{12}$ rephase $\boldsymbol{k}_\perp$-mismatched (i.e., "momentum spreading") at vicinity of specific incidence.
- Choice of δL depending on central incident Bragg-mismatch.
- For $k_\perp \to 0$, $\delta L = -1 + \pi/4$.
- Bloch-sphere representation of momentum echo at various δL.





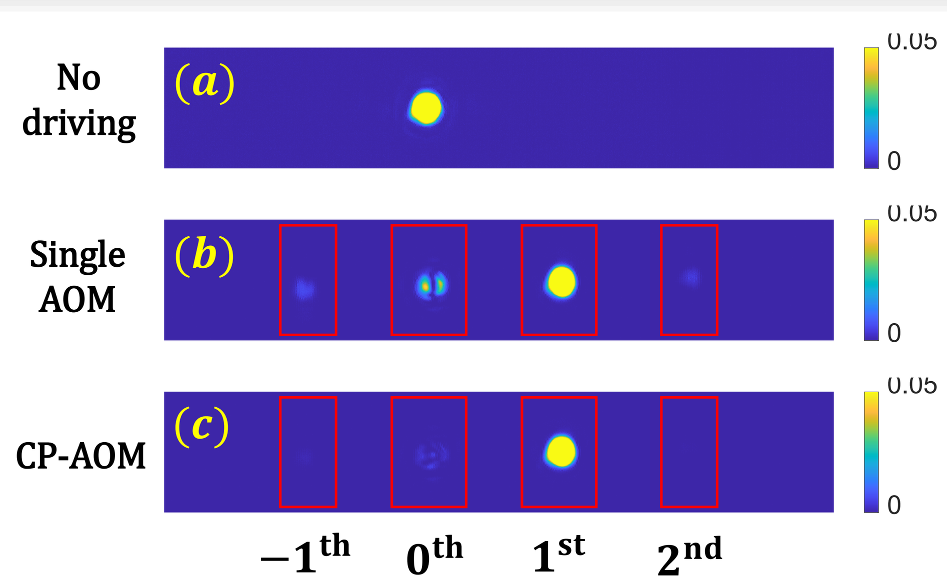
IV. High-Order Rephasing

$$H_0 \propto \begin{pmatrix} \left[\boldsymbol{k}_\perp + \frac{3}{2}\boldsymbol{k}_s\right]^2 & & & \\ & \left[\boldsymbol{k}_\perp + \frac{1}{2}\boldsymbol{k}_s\right]^2 & & \\ & & \left[\boldsymbol{k}_\perp - \frac{1}{2}\boldsymbol{k}_s\right]^2 & \\ & & & \left[\boldsymbol{k}_\perp - \frac{3}{2}\boldsymbol{k}_s\right]^2 \end{pmatrix}$$

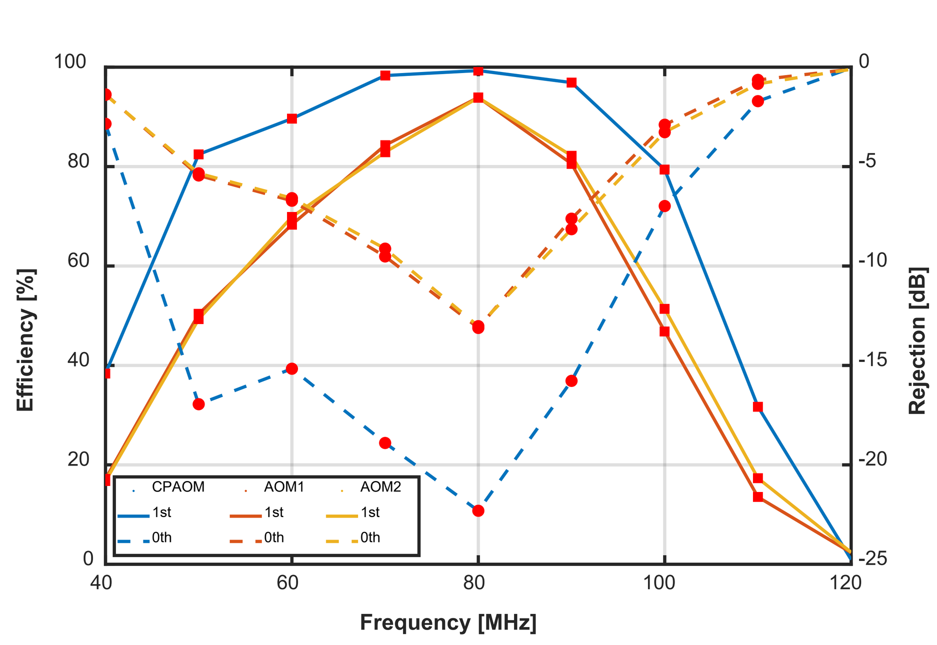


- Propagation phase of higher-order diffraction is approximately quantized by $\frac{k_S^2}{2\bar{n}k_0} \gg \frac{k_\perp k_S}{2\bar{n}k_0}$
- Fine adjustment of δL suppress specific high order m.
- m=-1, 2 almost rephase at the same δL

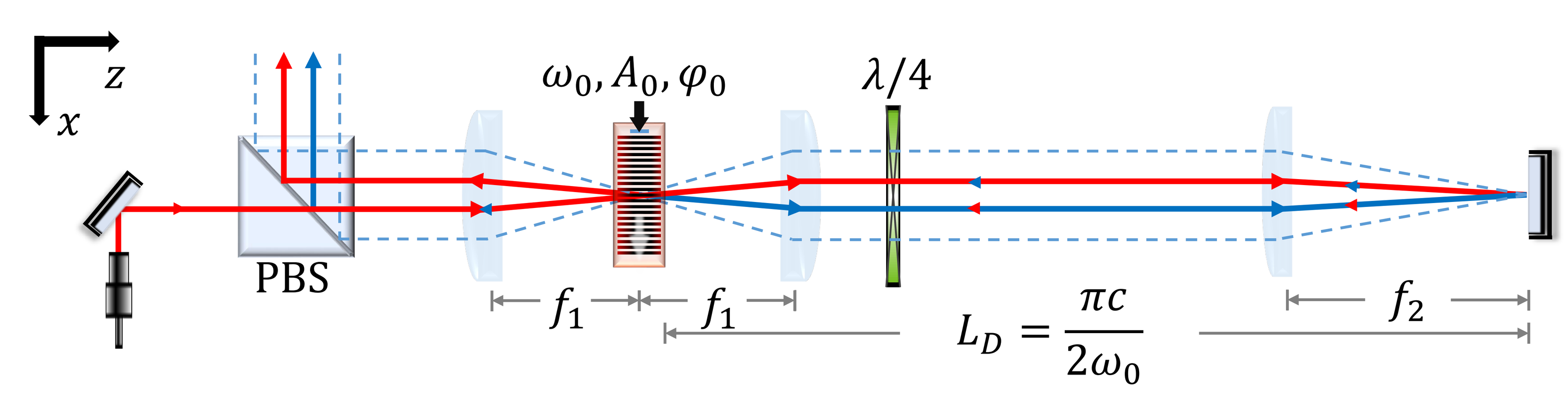
V. Experiment Results



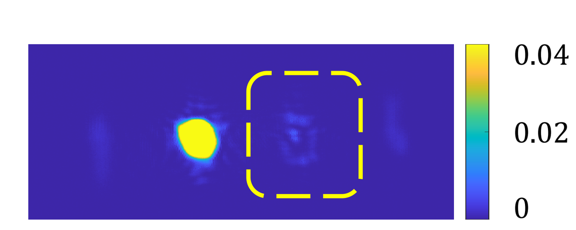
- Excellent diffraction efficiency(>99%)
- Suppressed high-order diffraction
- Wideband operation: Aligned at 80MHz, efficiency beyond 80% is achieved with a 50MHz bandwidth (+1 order).
- Efficient suppression of the 0th order (20dB free space, >35dB single mode fiber) supports optical routing on demand.



VI. Single-AOM implementation



- Sagnac Configuration
- Straightforward implementation with single-AOM rf electronics.



VII. Reference

[1] C. E. Rogers and P. L. Gould, Opt. Express, 24, 2596 (2016).
[2] R. Liu, Y. Ma, et al, Opt. Express 30(15), 27780-27793 (2022).

https://ultracontrol.fudan.edu.cn/main.htm