# Composite Acousto-Optical Diffraction with Efficiency Exceeding 99%

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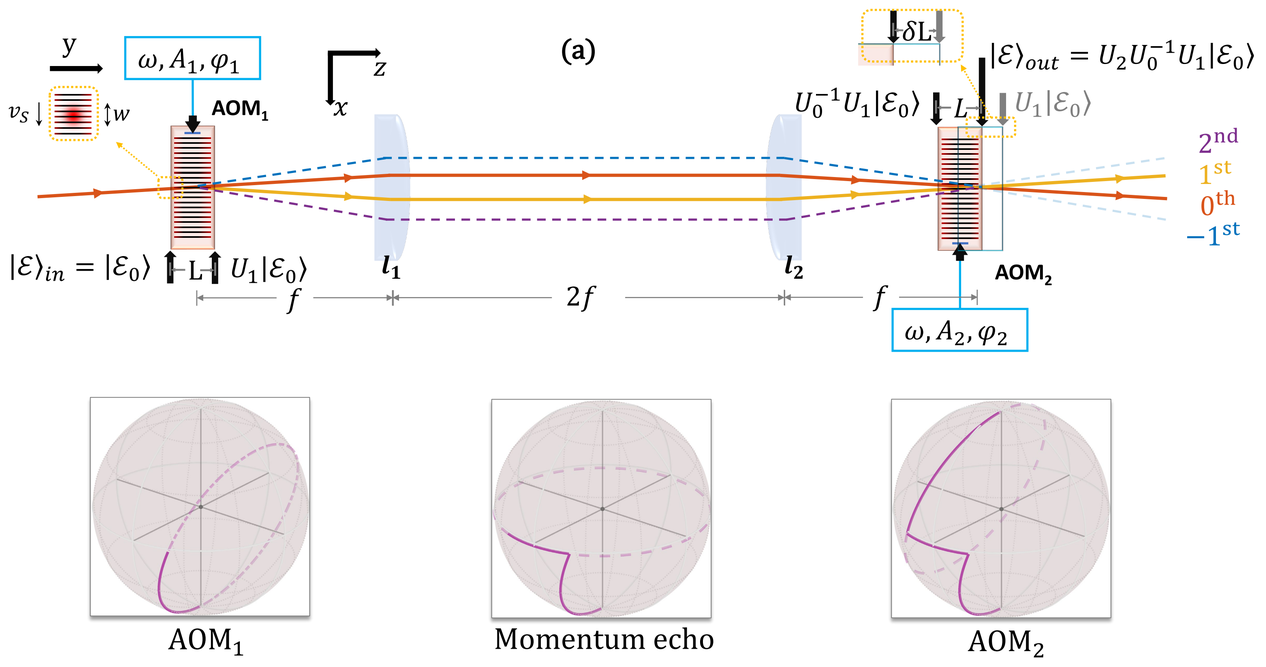
## I. Introduction

Acousto-optical modulation (AOM) is a powerful, widely applied technique for rapidly controlling frequency, phase, 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: $\mathcal{E} = \sum C_m e^{i(\boldsymbol{k}_\perp + m\boldsymbol{k}_S)\boldsymbol{r}_\perp}$

- **Raman-Nath equation**

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

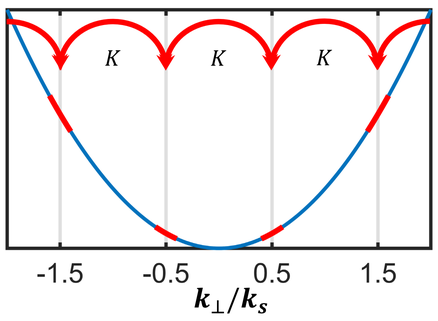
$K = \eta p k_0$

- **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**

$$U = U_2U_0^{-1}U_1$$

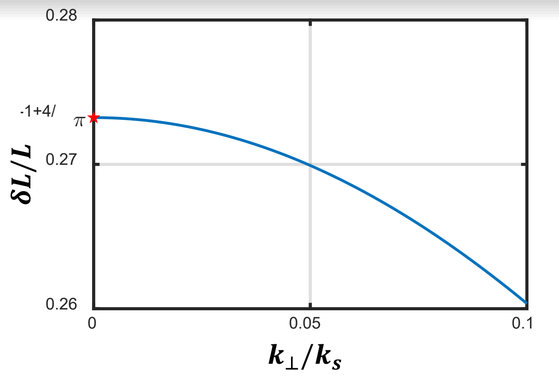
AOM$_1$: $U_1 = e^{-iH_1L}$

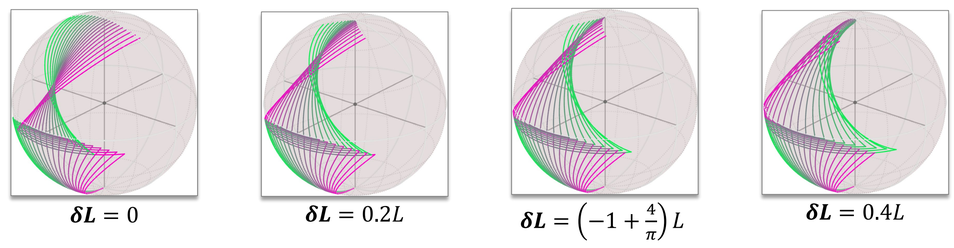
4-f imaging: $U_0^{-1} = e^{iH_0(L+\delta L)}$

AOM$_2$: $U_2 = e^{-iH_1L}$

## III. Momentum echo

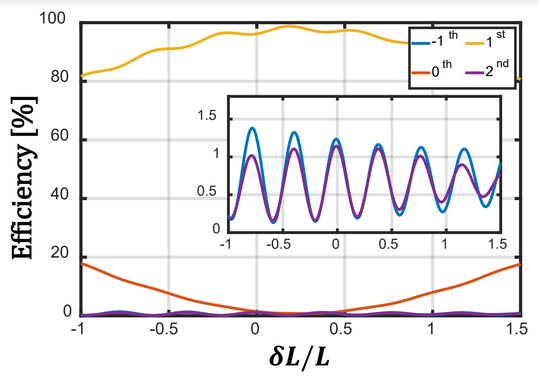
- Small relative displacement between AOM$_{12}$ rephase $\boldsymbol{k}_\perp$ -mismatched (i.e., "momentum spreading") at vicinity of specific incidence.
- Choice of $\delta L$ depending on central incident Bragg-mismatch.
- For $k_\perp \to 0$, $\delta L = -1 + \pi/4$.
- Bloch-sphere representation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



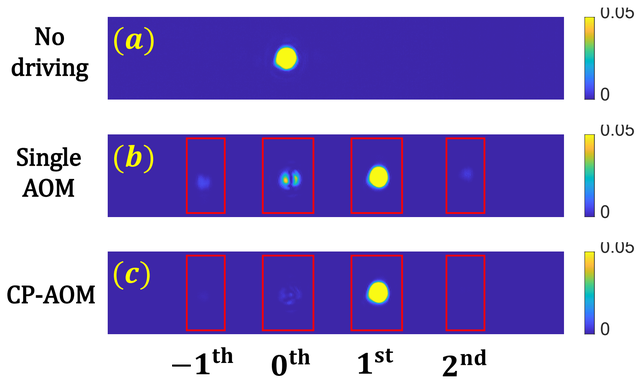

## IV. High-Order Rephasing

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

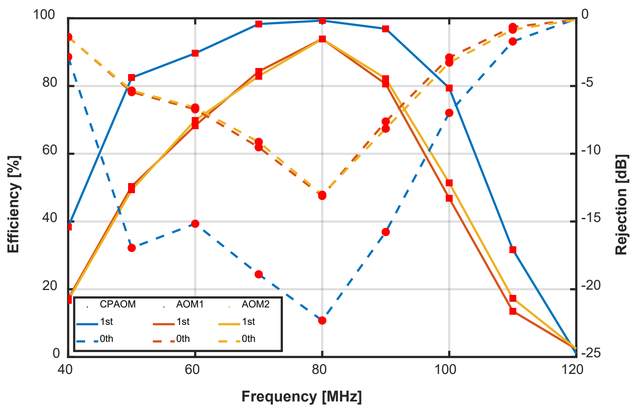



- Propagation phase of higher-order diffraction is approximately quantized by $\frac{k_S^2}{2\bar{n}k_0} \gg \frac{k_\perp k_S}{2\bar{n}k_0}$
- Fine adjustment of $\delta L$ suppress specific high order m.
- m=-1, 2 almost rephase at the same $\delta L$

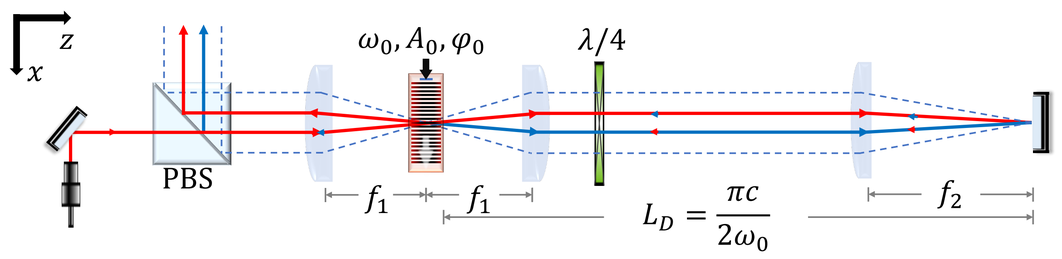
## V. Experiment Results




- 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