

Composite acousto-optical modulation for coherent pulse routing and stacking

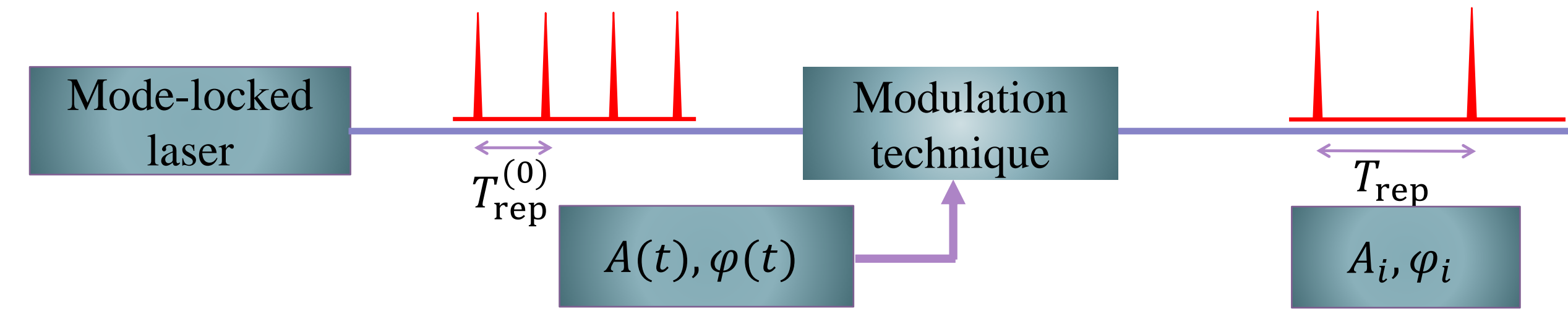
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Motivation: Full control of a mode-locked laser



Mode-locked lasers^[1] allow people to access physics at various time scales with finest precision. To fully utilize a mode-locked laser, one would like to arbitrarily modulate the pulsed output, including:

- Multiplying or dividing the repetition rate f_{rep} and $T_{\text{rep}} = 1/f_{\text{rep}}$ on demand;
- Controlling amplitude (A_i), phase (φ_i), and waveform shape of individual pulses.

T_{rep} -control: EOM&Pockels cell^[2] utilize electro-optical effects and can be ultrafast. However, the Pockels cells can hardly operate beyond a 10 MHz rate since it is difficult to generate the powerful high-voltage waveforms while managing the dissipation.

T_{rep} -control: AOM(s)^[3] utilize acoustic-optical effects associated with crystal vibration and are therefore slow. The diffraction efficiency relies on phase-matching the light beams with the sound waves. Deviation from the Bragg condition leads to reduced efficiency and distorted diffraction phases.

This work: We identify a class of composite AOM schemes based on interference of diffraction orders by multiple AOMs. The light diffraction dynamics is mapped to matterwave dynamics in a pulsed standing wave potential, a scenario frequently visited in atom interferometry community^[4,5]. Many ideas for robust matterwave control can be transferred to AOM diffraction beyond traditional pictures of applications. In this work, we adjust the amplitudes and phases of weakly-driven daughter AOMs, a 2-mode approximation maps the composite diffraction dynamics to time-domain spin control, where composite pulse techniques are developed to universally enhance the resilience to the control errors.

We provide a proof-of-principle demonstration with a simplest example using two AOMs. The new scheme supports high-efficiency control of CW and pulsed lasers with ultra-wideband rf tuning range, and allows phase coherent routing of the output at the driving rf frequency limit. After the f_{rep} -pre-scaling, we further demonstrate free-space coherent stacking of adjacent pulses with a beamsplitter (BS), after optically bridging the T_{rep} delay, with $\sim 90\%$ energy efficiency. Taking advantage of MHz-level control bandwidth for active feedback, the coherent pulse routing and stacking can operate well in noisy environments^[6].

[1] H. A. Haus, IEEE J. Select. Topics Quantum Electron. 6(6), 1173 (2000).

[2] E. A. Donley et al, Rev. Sci. Instrum. 76(6), 063112 (2005).

[3] J. Thom et al, Opt. Express 21(16), 18712 (2013).

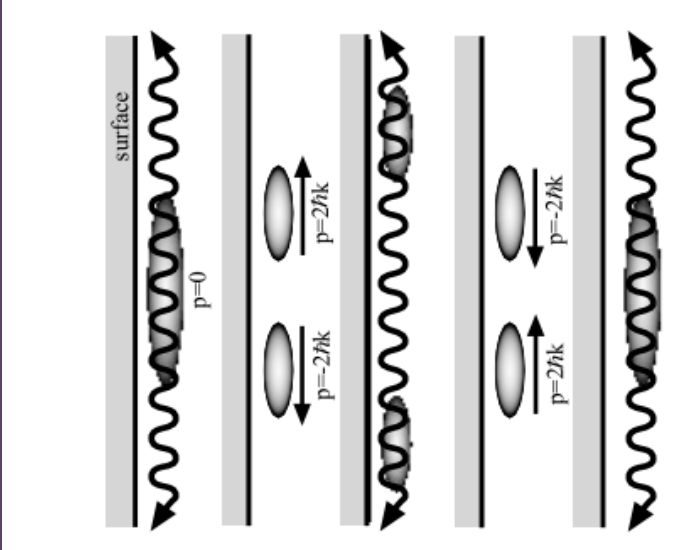
[4] Y.-J. Wang et al, Phys. Rev. Lett. 94(9), 090405 (2005).

[5] S. Wu, Phys. Rev. A 71(4), 043602 (2005).

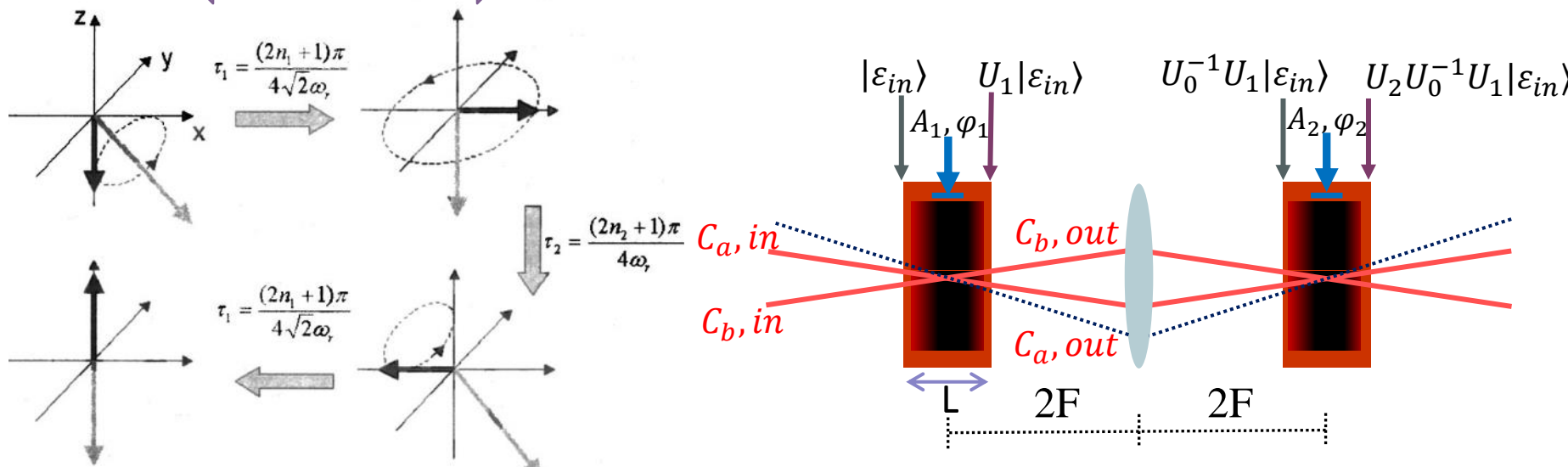
[6] R. Liu et al, Opt. Express 30(15), 27780 (2022).

Simplest example: double-diffraction

Matter-wave double-diffraction^[4]



AOM double-diffraction^[6]



Atom in a standing-wave potential, Schrödinger's equation is given by,

$$i\hbar\partial_t\psi(x,t) = \left(-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + \Omega(t)\cos(2k_0x)\right)\psi(x,t)$$

By expanding the wave function in the Bloch basis, we have,

$$i\hbar\partial_t C_{2n}(k,t) = \frac{\hbar}{2m}(2nk_0+k)^2 C_{2n}(k,t) + \frac{\Omega(t)}{2}[C_{2n-2}(k,t) + C_{2n+2}(k,t)]$$

For weak excitations, the dynamics reduces to a two-state model,

$$i\hbar\dot{C}_0 = -2\omega_r C_0 + \frac{\Omega(t)}{\sqrt{2}} C_+$$

$$i\hbar\dot{C}_+ = \frac{\Omega(t)}{\sqrt{2}} C_0 + 2\omega_r C_+$$

Many schemes exist for the 2-level^[6] and multi-level^[7] coherent controls.

[6] Low et al PRX 6, 041067 (2016).

[7] Cronin et al Rev. Mod. Phys. 81, 1051 (2009).

The light diffracted by two AOMs can be optically linked via a 4F imaging system. Paraxial light propagation in the AOM as:

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

$$\delta n = \eta p \frac{1 - \bar{n}^2}{2\bar{n}} \cos(k_s x - \omega_s t + \varphi)$$

Let's consider Bragg-resonantly coupled zeroth and first order diffractions. By ignoring off-resonant orders for weakly-driven AOMs, the dynamics of light is also reduced to,

$$i\partial_z C_a = \frac{(k_{\perp} - k_s/2)^2}{2\bar{n}k_0} C_a + \frac{K}{2} C_b$$

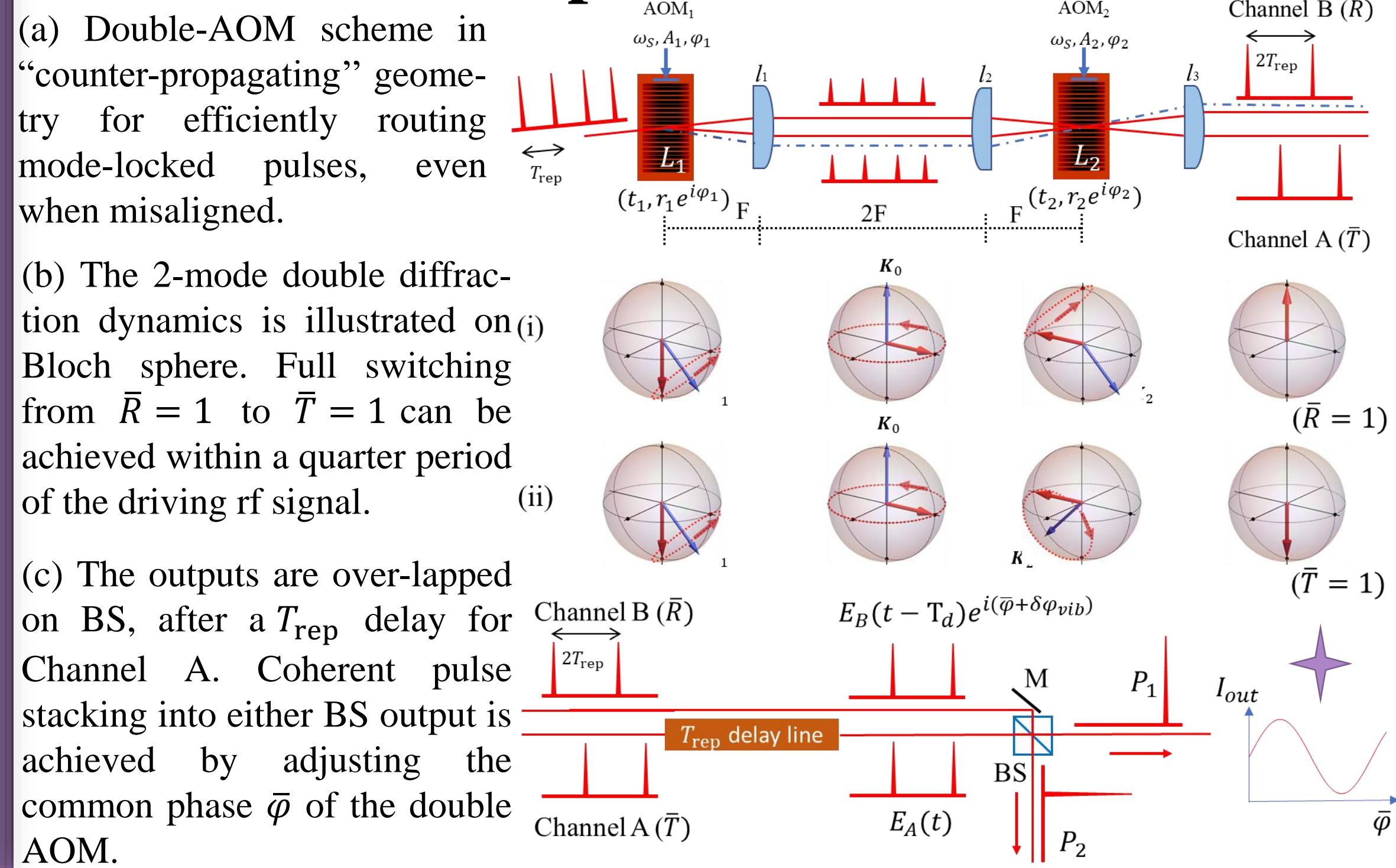
$$i\partial_z C_b = \frac{(k_{\perp} + k_s/2)^2}{2\bar{n}k_0} C_b + \frac{K}{2} C_a$$

The constant $K = \frac{\eta p k_0 (\bar{n}^2 - 1)}{2\bar{n}}$ is a "spatial Rabi frequency"^[5].

The input-output relation $|\mathcal{E}_{\text{out}}\rangle = U|\mathcal{E}_{\text{in}}\rangle$ are applied for 4F-linked AOMs as shown in the figure. Here $U_j = U(t_j, r_j e^{i\varphi_j})$, U_0^{-1} effectively evolves the wavefront backward for dispersion

compensation. The method can be applied iteratively to supports $\sim 99\%$ -level diffraction efficiency.

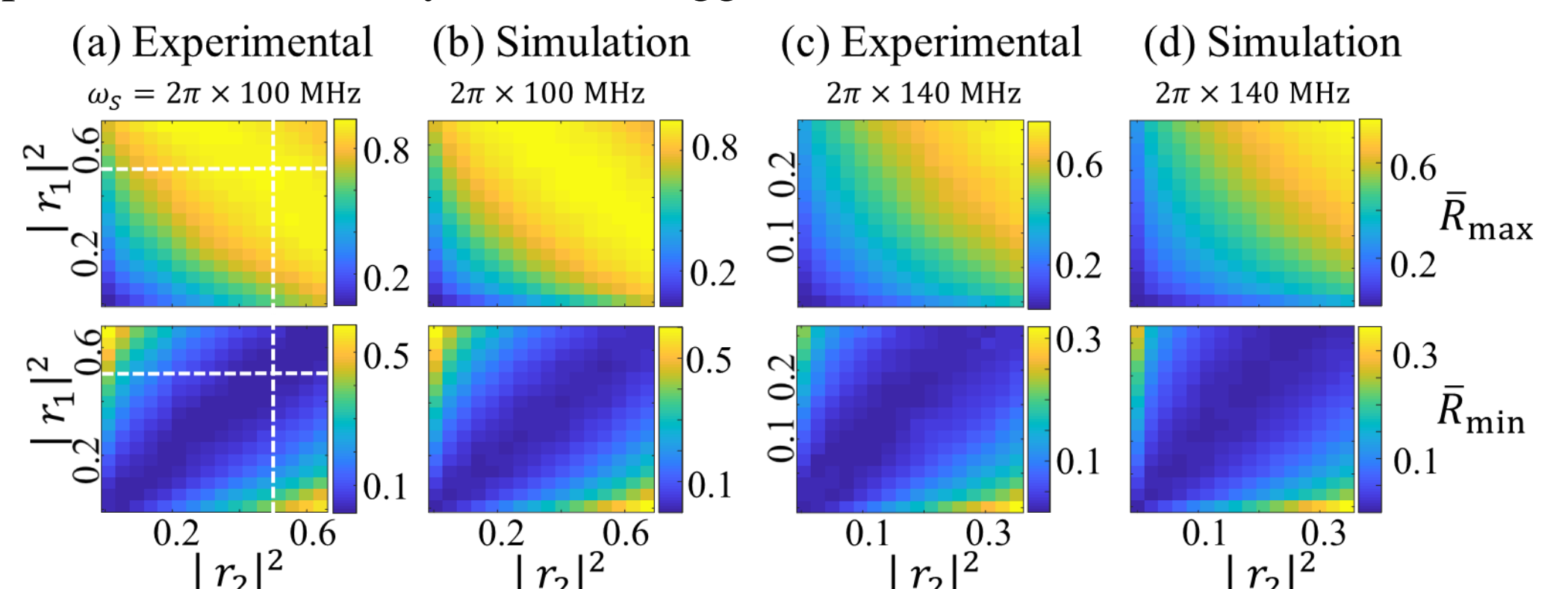
A Proof-of-Principle demonstration



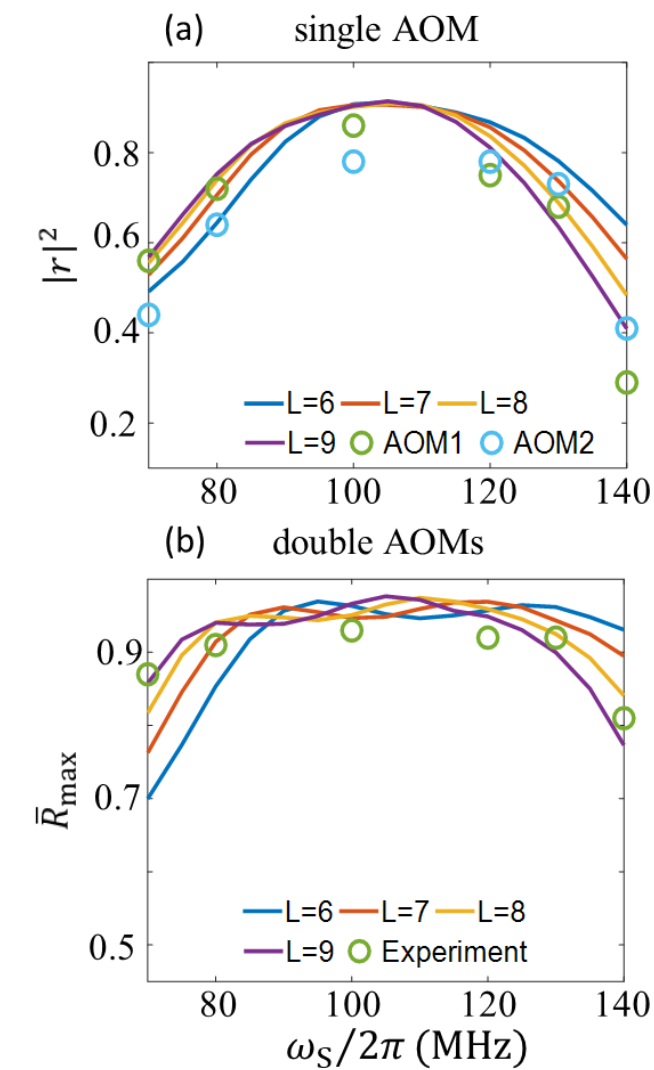
Results

• Typical pulsed laser outputs ($\omega_s = 2\pi \times 80\text{MHz}$, 20MHz off)

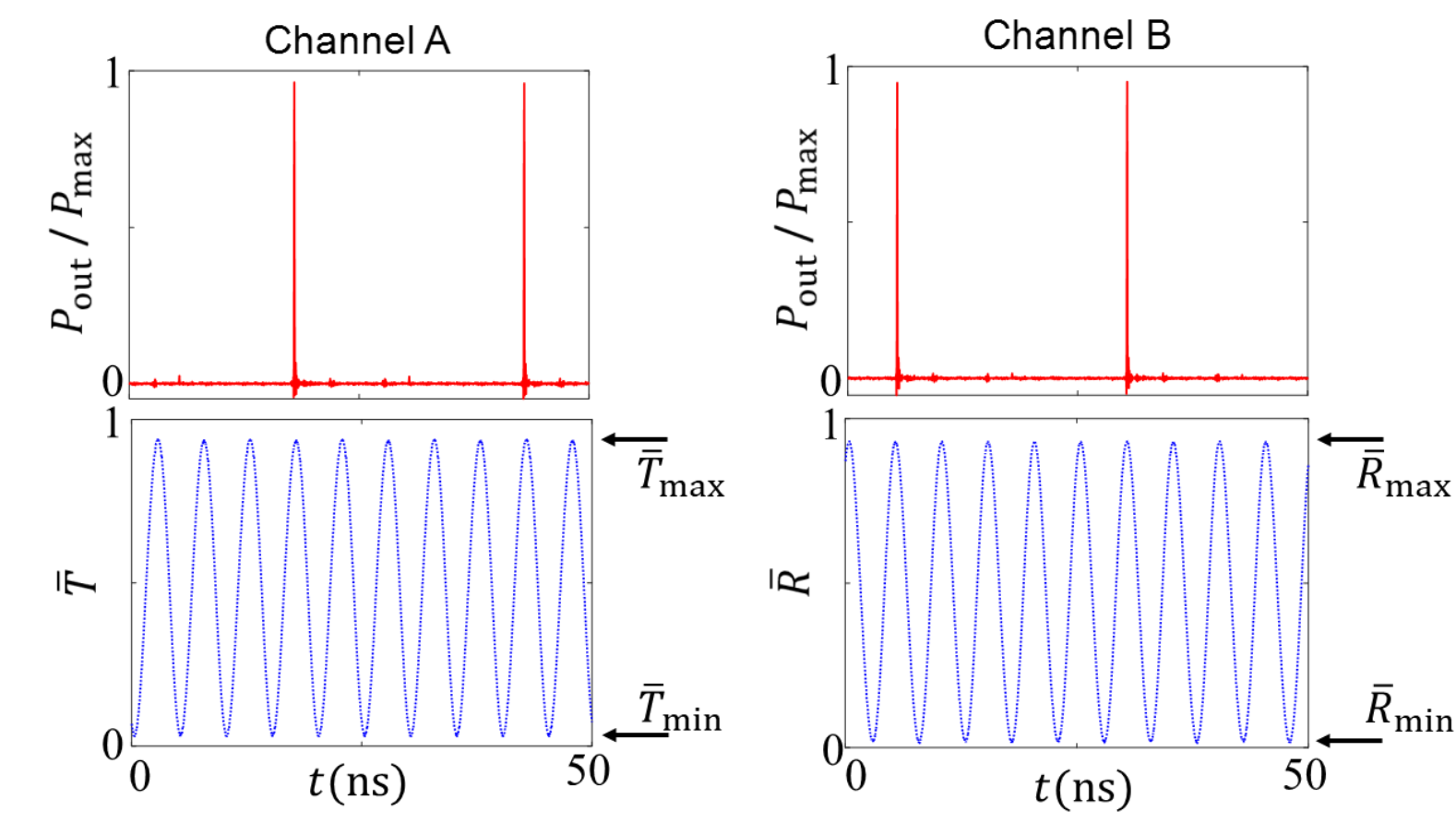
• Operation near and beyond the Bragg condition



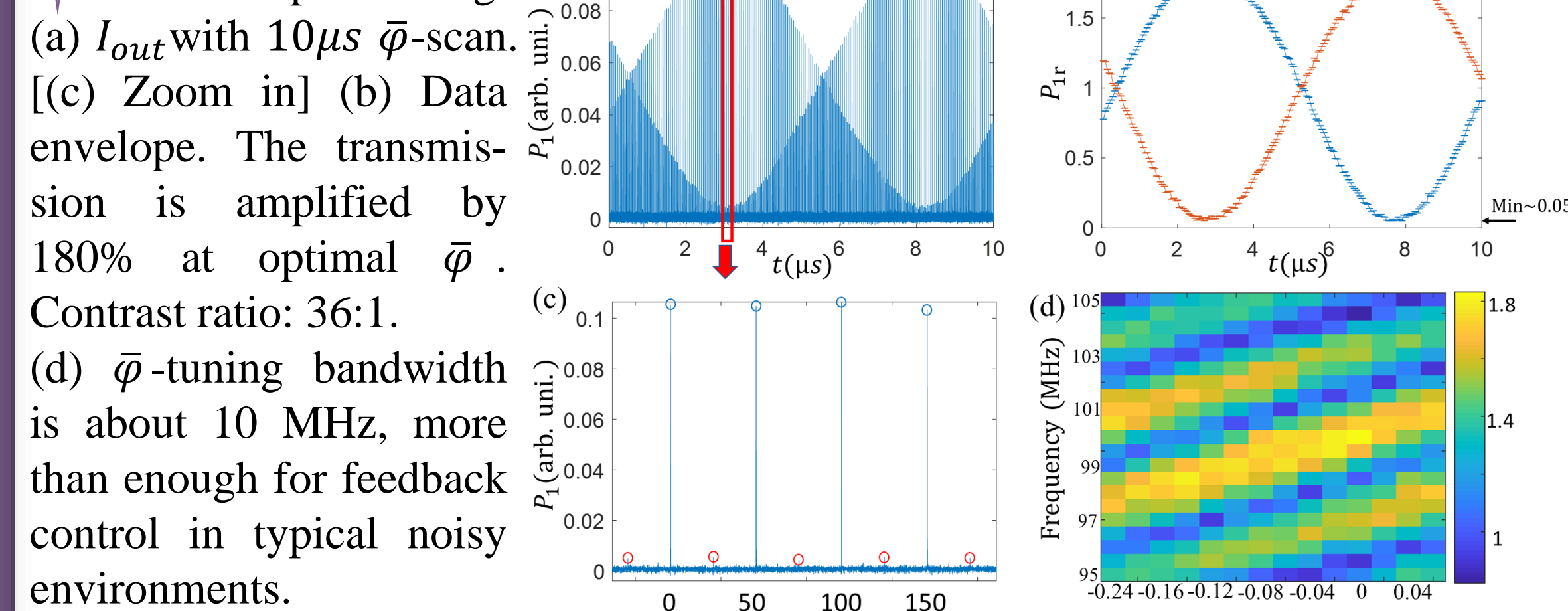
• Wideband operation: influence of AOM acoustic interaction length



- Pulse picking within 2.5 nanosecond
- Efficiency: 96% (A) and 94% (B)
- Contrast: 30:1 (A) and 100:1 (B)



• Coherent ps stacking:



Applications:

• **CEP control**

The AOM scheme in this work can provide broad bandwidth and high diffraction efficiency for stabilizing the carrier-envelope phase (CEP) of a few-cycle pulse, in combination of the efficient and stable pulse compression technique recently developed. (Zhang *et al.* Light: Science & Applications 10, 53 (2021)).

• **Fast nonlinear imaging**

Rapid switching of polarization states in a pulse-to-pulse manner facilitates various applications in coherent nonlinear imaging, such as for probing Raman optical activity (ROA) of chiral molecules.

• **Quantum control of strong transitions**

A multi-path routing and time-domain multiplexing network can be constructed by iterative application of the demonstrated scheme, for generating GHz-rep-rate coherent pulses, individually shaped, for robust control of electric dipole spin wave.