Composite acousto-optical modulation for coherent pulse routing and stacking

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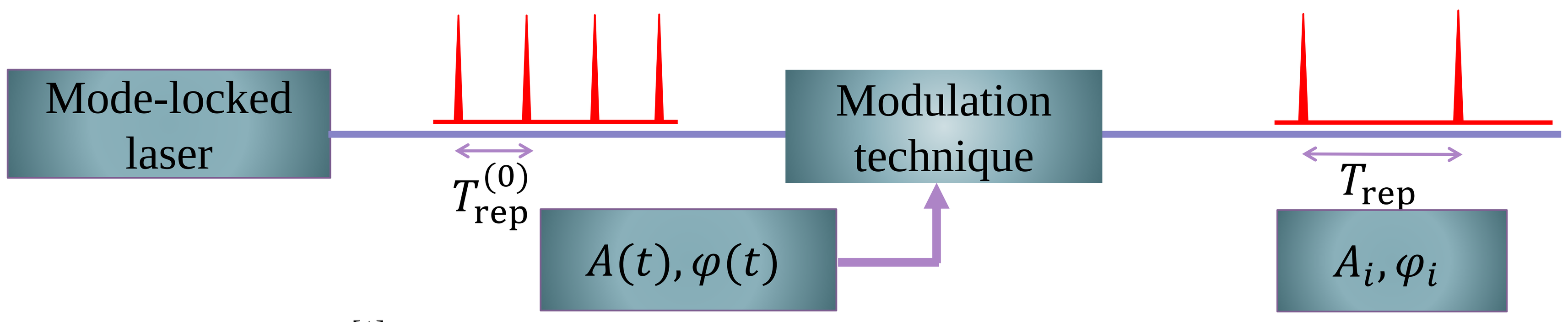
Motivation: Full control of a mode-locked laser



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 $f_{\rm rep}$ and $T_{\rm rep} = 1/f_{\rm rep}$ on demand;
- Controlling amplitude (A_i), phase (φ_i), and waveform shape of individual pulses.

$T_{\rm rep}$-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.

$T_{\rm rep}$-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.

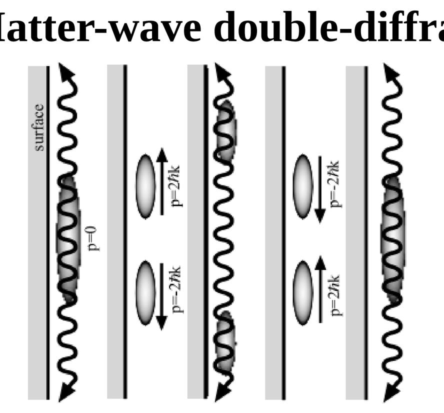
This work: We identify a class of composite AOM schemes based on interference of diffraction orders by multiple AOMs. The light diffraction dynamics is mapped to matterwave dynamics in a pulsed standing wave potential, a scenario frequently visited in atom interferometry community[4,5]. Many ideas for 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.

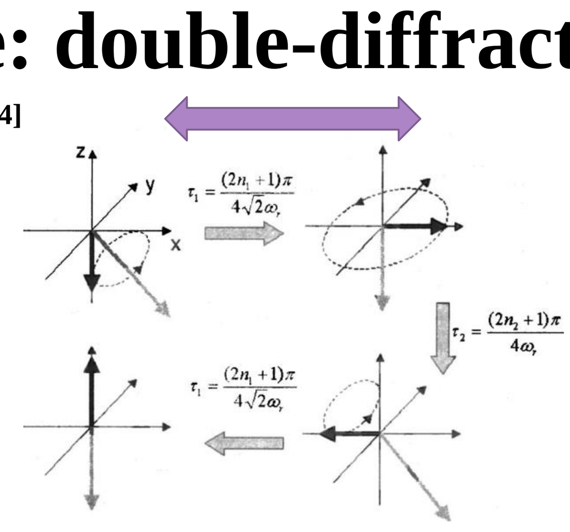
We provide a proof-of-principle demonstration with a simplest example using two AOMs. The new scheme supports high-efficiency control of CW and pulsed lasers with ultra-wideband rf tuning range, and allows phase coherent routing of the output at the driving rf frequency limit. After the $f_{\rm rep}$-pre-scaling, we further demonstrate free-space coherent stacking of adjacent pulses with a beamsplitter (BS), after optically bridging the $T_{\rm rep}$ delay, with ~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 etal, 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).

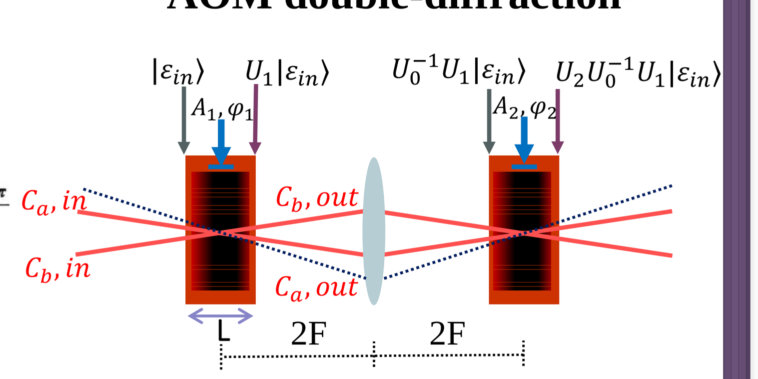
Simplest example: double-diffraction

Matter-wave double-diffraction [4]





AOM double-diffraction[6]



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

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

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

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

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

$$i\dot{C}_0 = -2\omega_rC_0 + \frac{\Omega(t)}{\sqrt2}C_+$$

$$i\dot{C}_+ = \frac{\Omega(t)}{\sqrt2}C_0 + 2\omega_rC_+$$

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:

$$i\partial_z\mathcal{E} = -\frac{1}{2\bar nk_0}\nabla_\perp^2\mathcal{E} - \delta nk_0\mathcal{E},\ \text{with}$$

$$\delta n = \eta p\frac{1-\bar n^2}{2\bar n}\cos(k_Sx-\omega_St+\varphi)$$

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,

$$i\partial_zC_a = \frac{(k_\perp-k_s/2)^2}{2\bar nk_0}C_a + \frac{K}{2}C_b$$

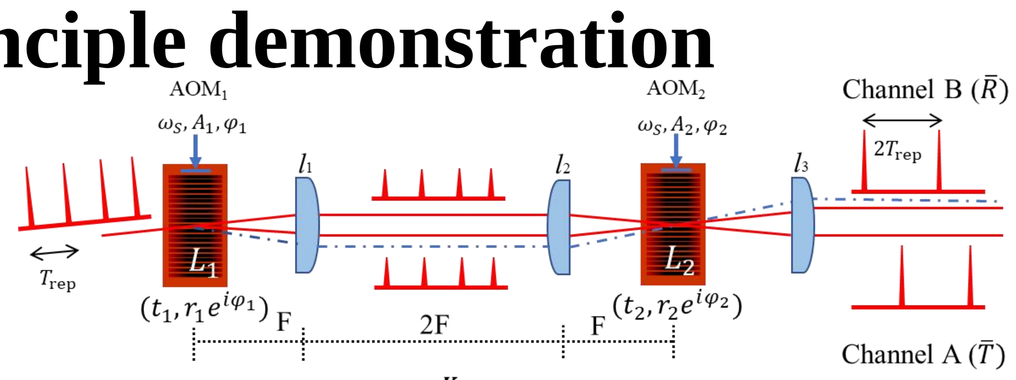
$$i\partial_zC_b = \frac{(k_\perp+k_s/2)^2}{2\bar nk_0}C_b + \frac{K}{2}C_a$$

The constant $K = \frac{\eta pk_0(\bar n^2-1)}{2\bar n}$ is a "spatial Rabi frequency"[5].

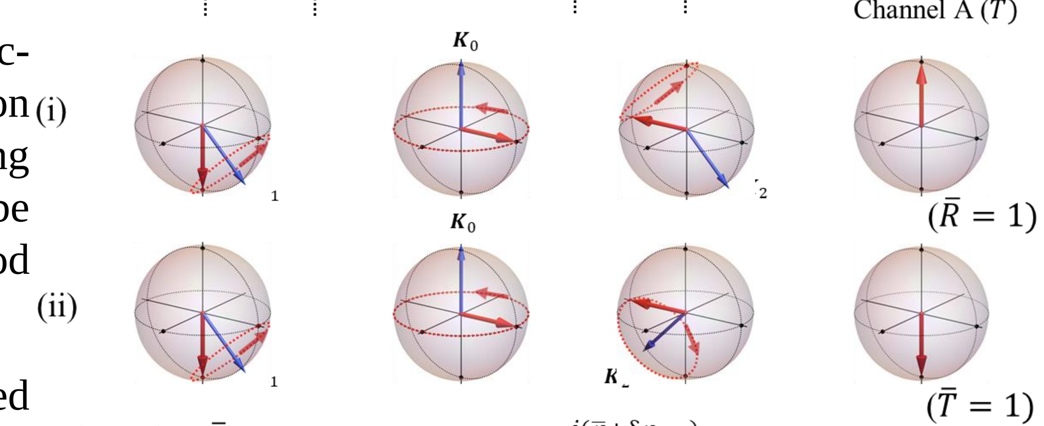
The input-output relation $|\mathcal{E}_{out}\rangle = \mathrm{U}|\mathcal{E}_{in}\rangle$ are applied for 4F-linked AOMs as shown in the figure. Here $U_j = U(t_j\,r_je^{i\varphi_j})$, U_0^{-1} effectively evolves the wavefront backward for dispersion compensation. The method can be applied iteratively to supports ~99%-level diffraction efficiency.

A Proof-of-Principle demonstration

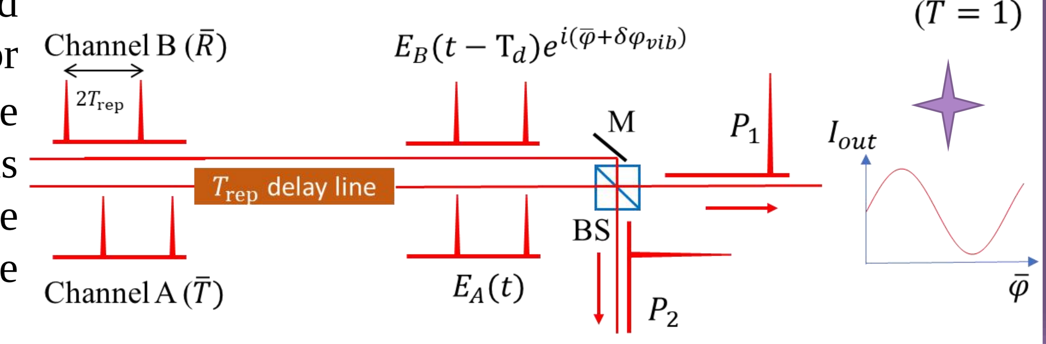
(a) Double-AOM scheme in "counter-propagating" geometry for efficiently routing mode-locked pulses, even when misaligned.



(b) The 2-mode double diffraction dynamics is illustrated on Bloch sphere. Full switching from $\bar R = 1$ to $\bar T = 1$ can be achieved within a quarter period of the driving rf signal.

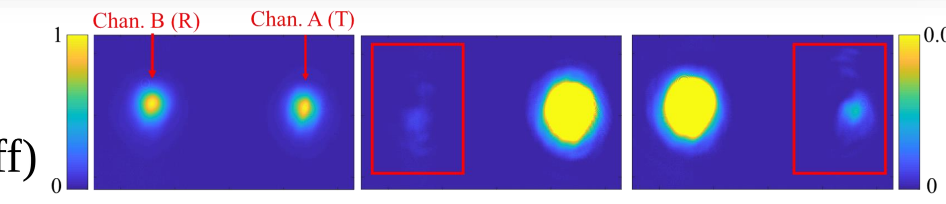


(c) The outputs are over-lapped on BS, after a $T_{\rm rep}$ delay for Channel A. Coherent pulse stacking into either BS output is achieved by adjusting the common phase $\bar\varphi$ of the double AOM.

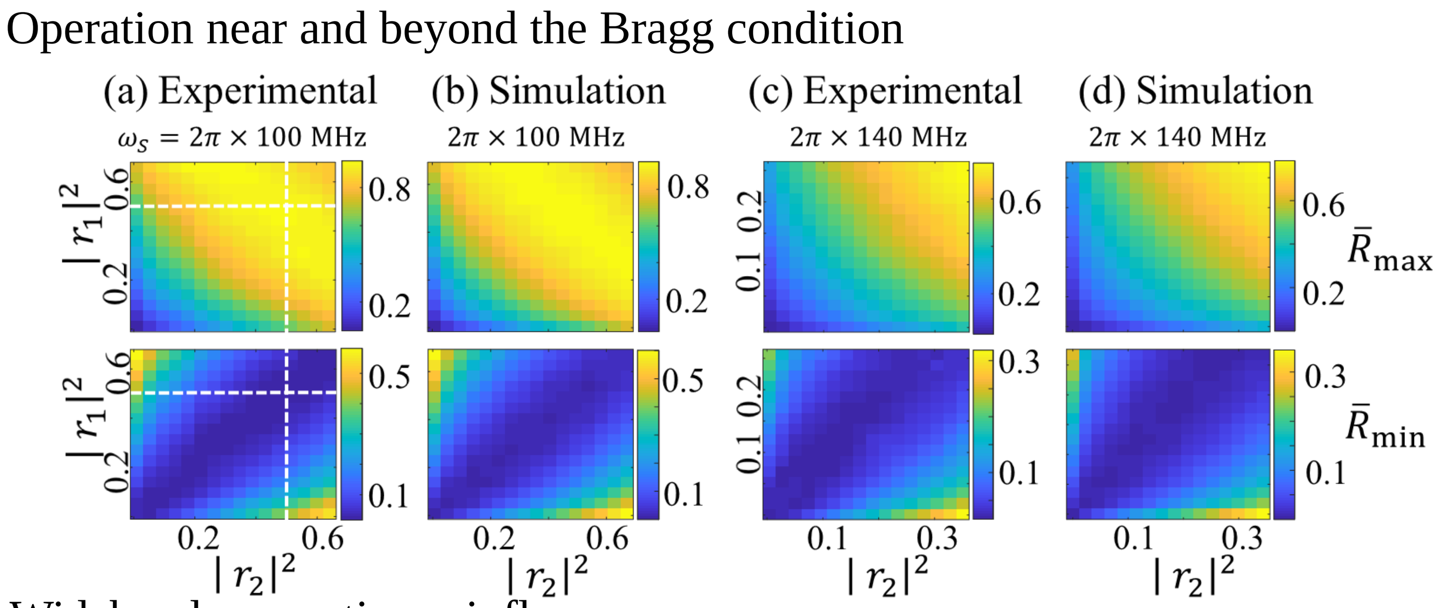


Results

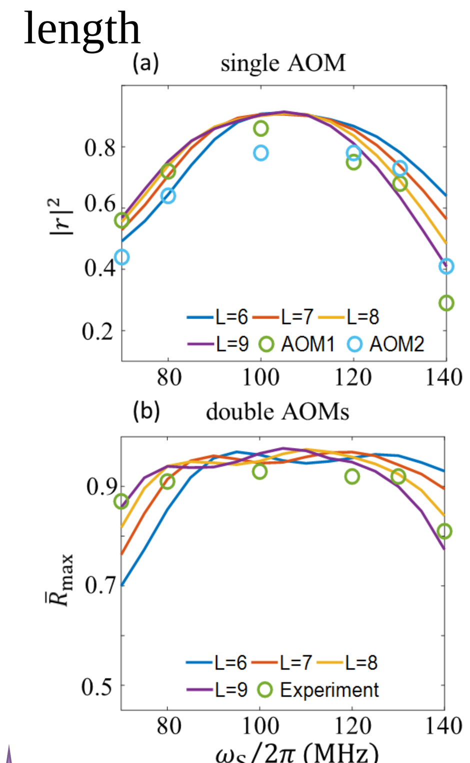
- Typical pulsed laser outputs ($\omega_S = 2\pi \times$80MHz, 20MHz off)



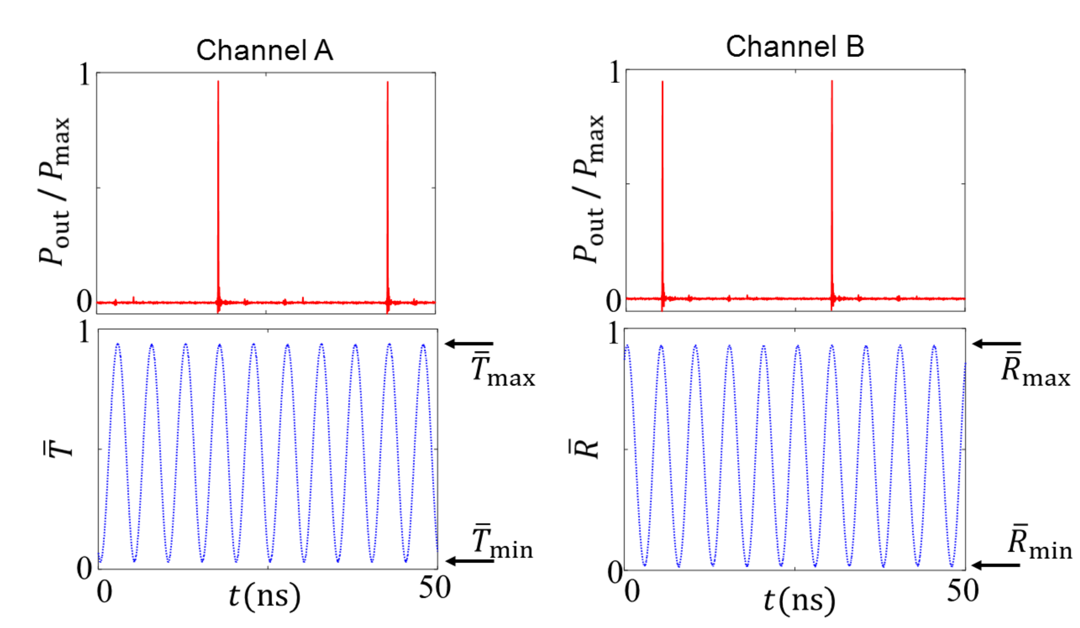
- Operation near and beyond the Bragg condition



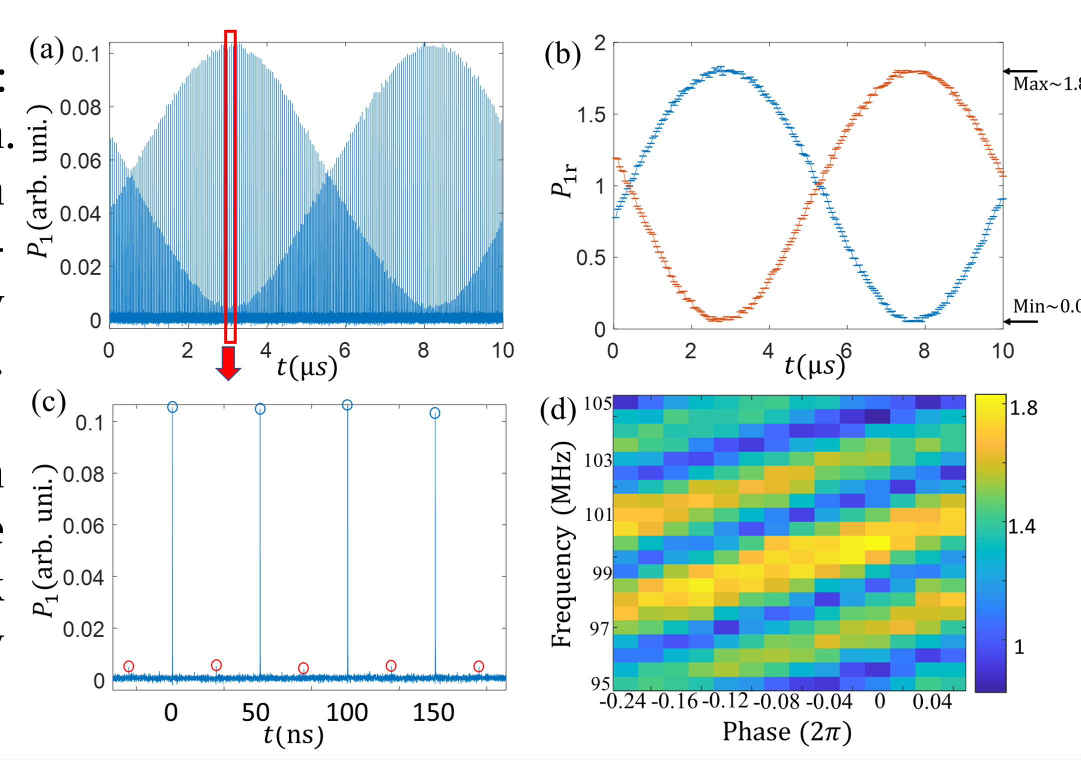
- Wideband operation: influence of AOM acoustic interaction length



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



Coherent ps stacking: (a) I_{out} with 10μs $\bar\varphi$-scan. [(c) Zoom in] (b) Data envelope. The transmission is amplified by 180% at optimal $\bar\varphi$. Contrast ratio: 36:1. (d) $\bar\varphi$-tuning bandwidth is about 10 MHz, more than enough for feedback control in typical noisy environments.



Applications:

- **CEP control**

The AOM scheme in this work can provide broad bandwidth and high diffraction efficiency for stabilizing the carrier-envelop 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.

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