Measurement and Synthesis of Ultrafast Scalar and Vectorial Optical Arbitrary Waveforms

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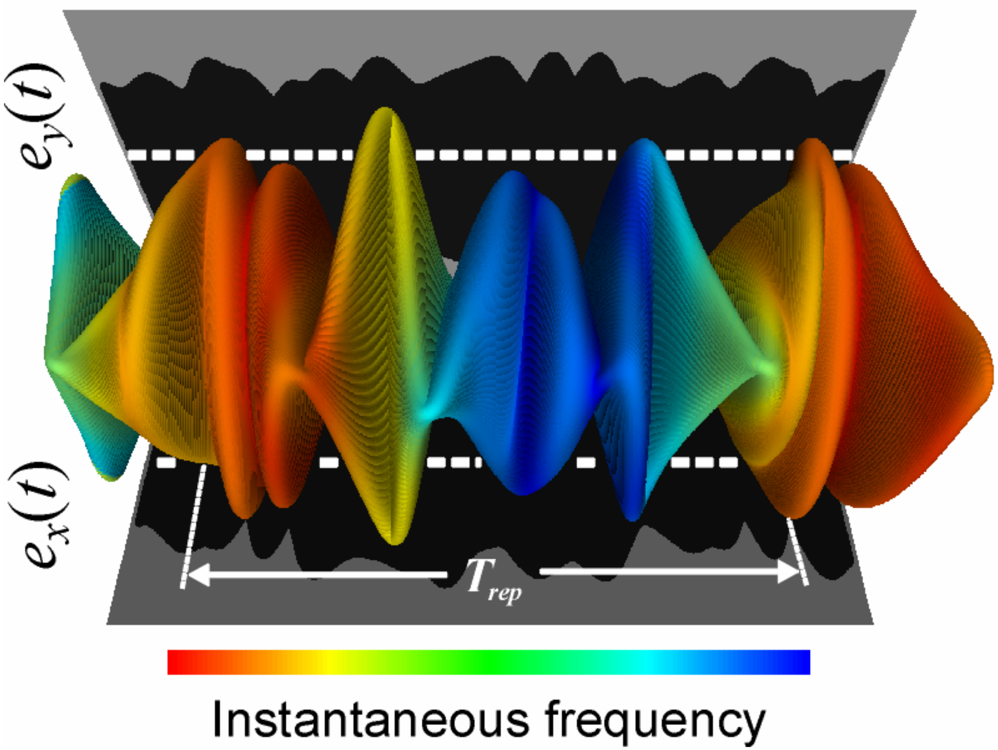
Ultrafast Photonics Lab

Overview

- Vectorial optical arbitrary waveform (V-OAW): E-field with transient amplitude, phase, polarization and 100% duty cycle.



Outline

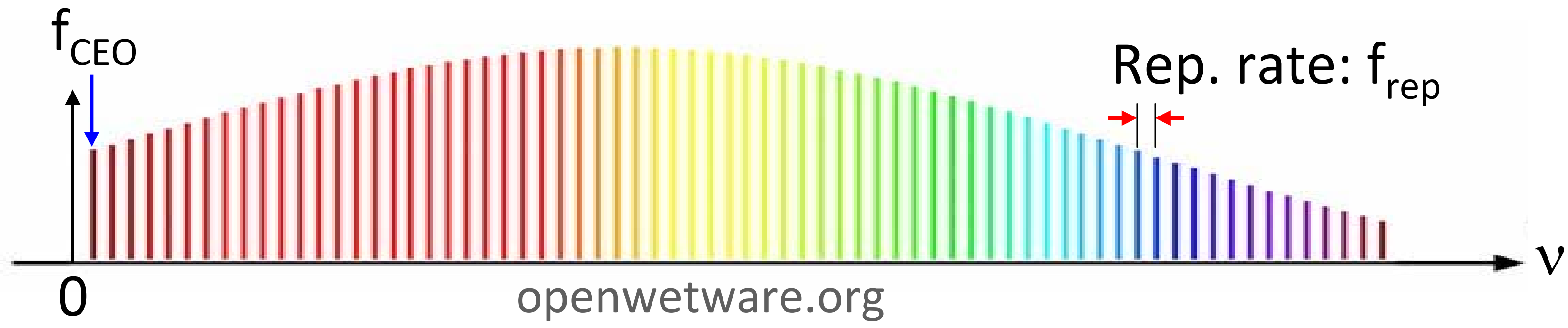
- Background
- Scalar OAW measurement: Orthogonally probed DQ-SSI
- Vectorial OAW measurement: VECTOR
- Conclusions

Part 1

- Background
- Scalar OAW measurement: Orthogonally probed DQ-SSI
- Vectorial OAW measurement: VECTOR
- Conclusions

Optical frequency comb

- A grid of fixed, equi-spaced spectral lines



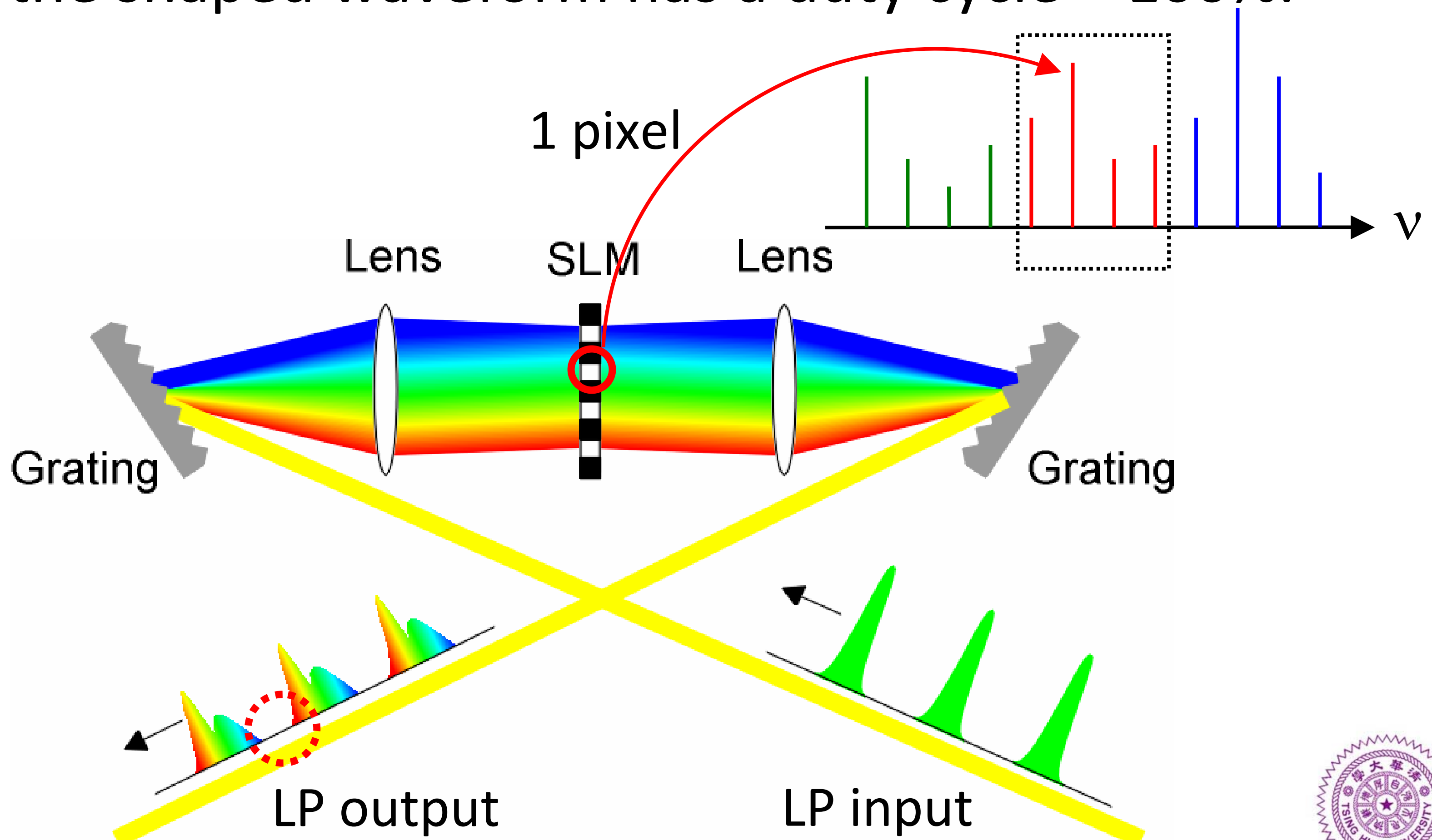
- How to generate?

1. f_{CEO}-locked pulse laser (f_{rep} ~ 100 MHz)
2. Phase-modulated CW (PMCW) comb (f_{rep} ~ 10 GHz)
3. High-Q cavity Kerr frequency comb (f_{rep} ~ 1 THz)

Group-of-line scalar pulse shaper

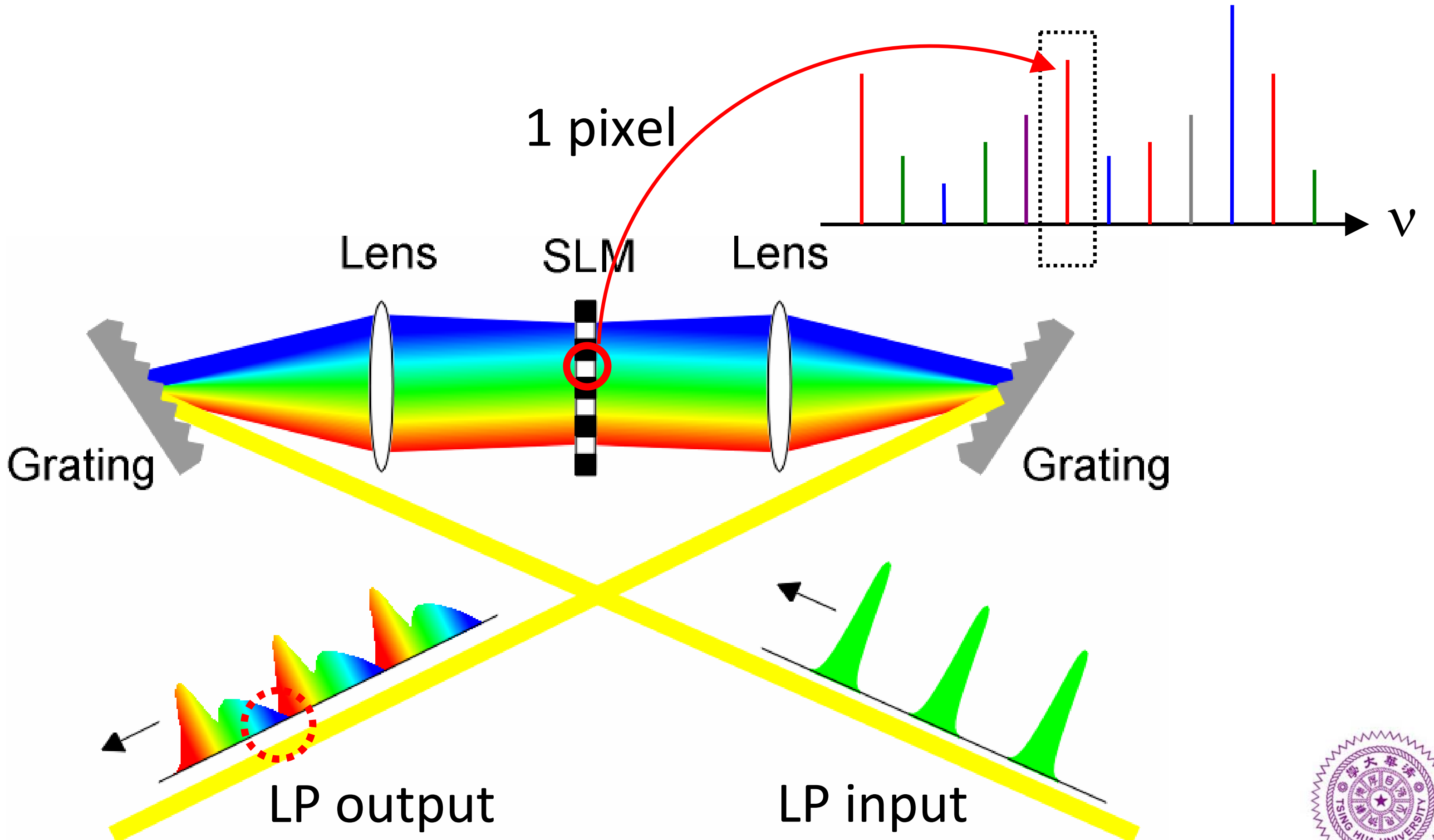
- One pixel modulates multiple spectral lines,

  $\Rightarrow$ the shaped waveform has a duty cycle < 100%.



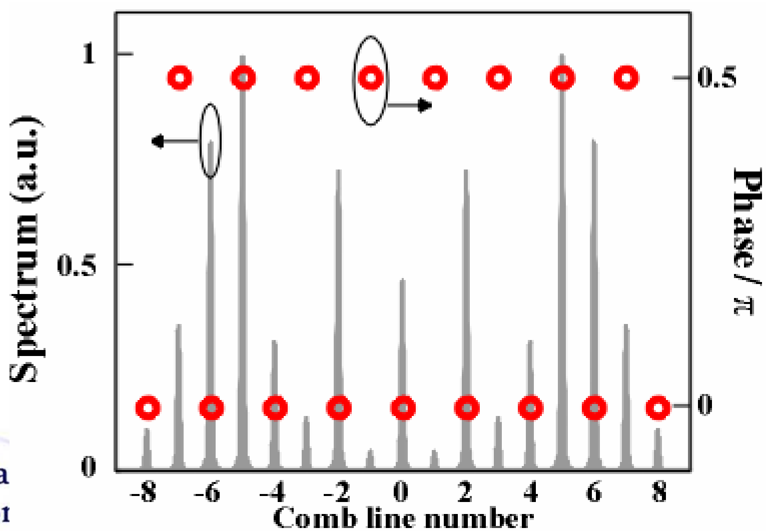
Line-by-line (LBL) scalar pulse shaper

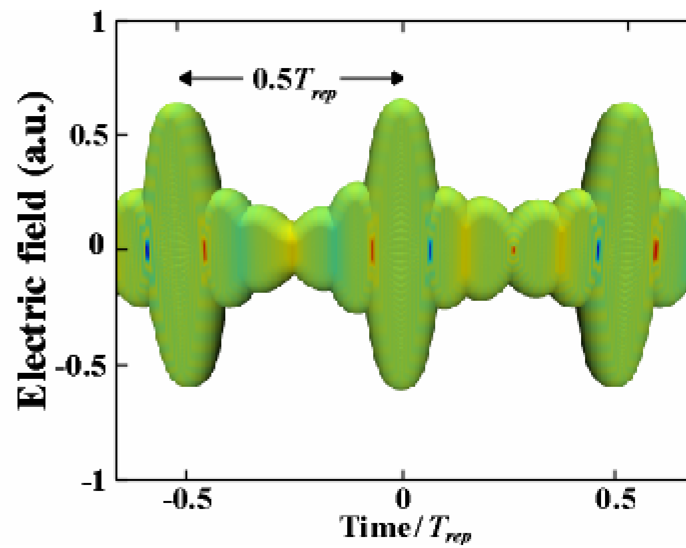
- One pixel only modulates one spectral line, $\Rightarrow$ the shaped waveform may have 100% duty cycle.



Scalar Optical Arbitrary Waveform

- (Optical frequency comb) + (LBL scalar pulse shaper) → scalar OAW
- Waveform can fill the entire time axis
- Intensity repetition rate can be multiplied (temporal Talbot effect)

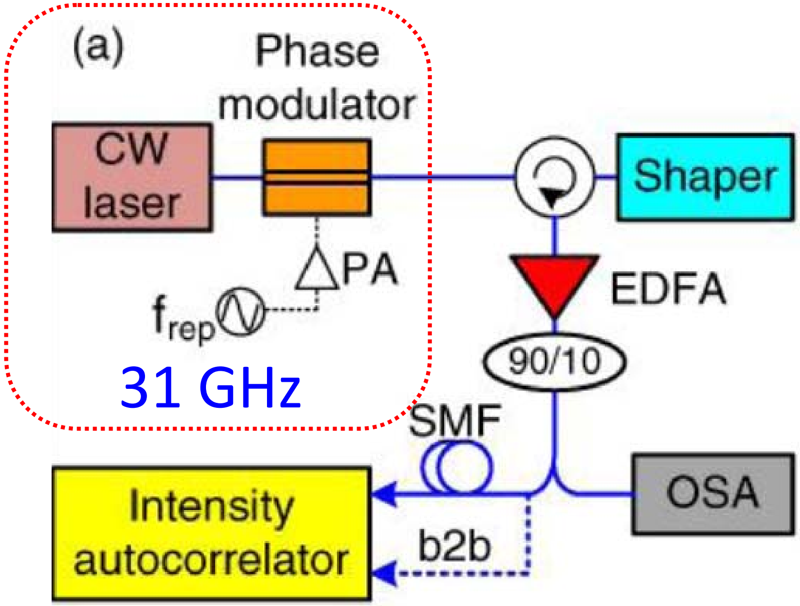


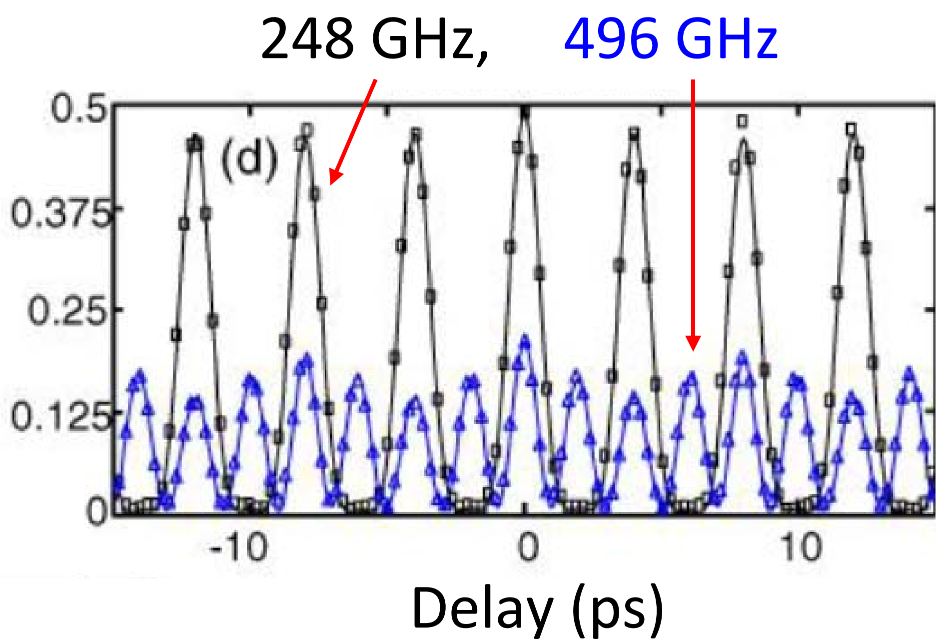


Ultrafa Photo

Application of scalar OAW

- 31 GHz → 496 GHz, delivered over 25 km fiber link,
  ⇒ radio-over-fiber communications



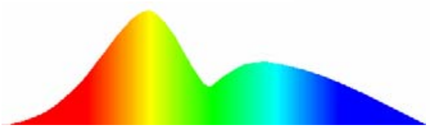


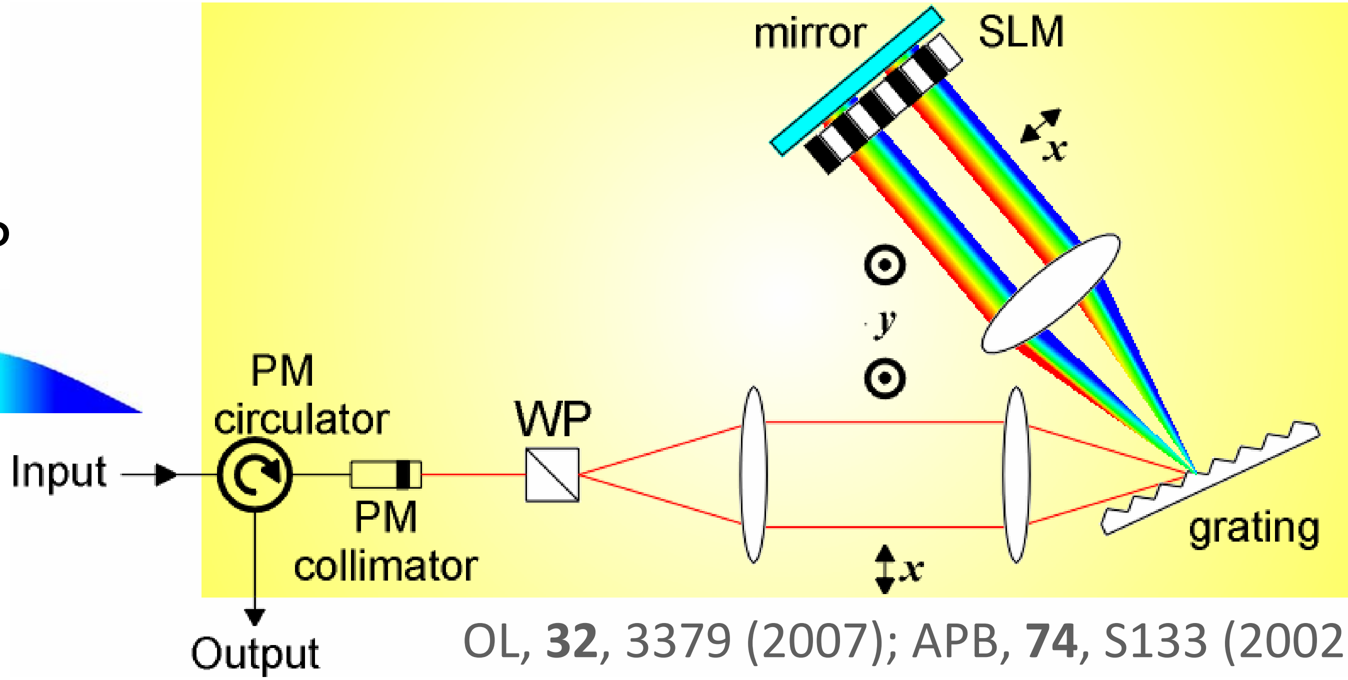
OE, **18**, 24003 (2010)

Polarization pulse shaper

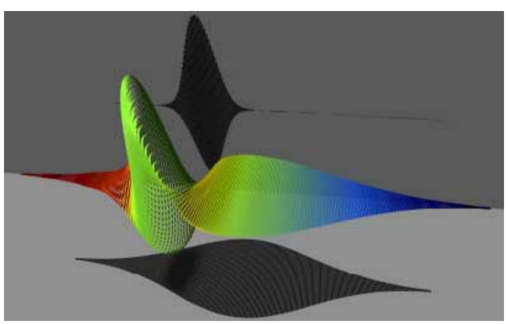
- x- and y-polarizations are independently controlled

45° LP





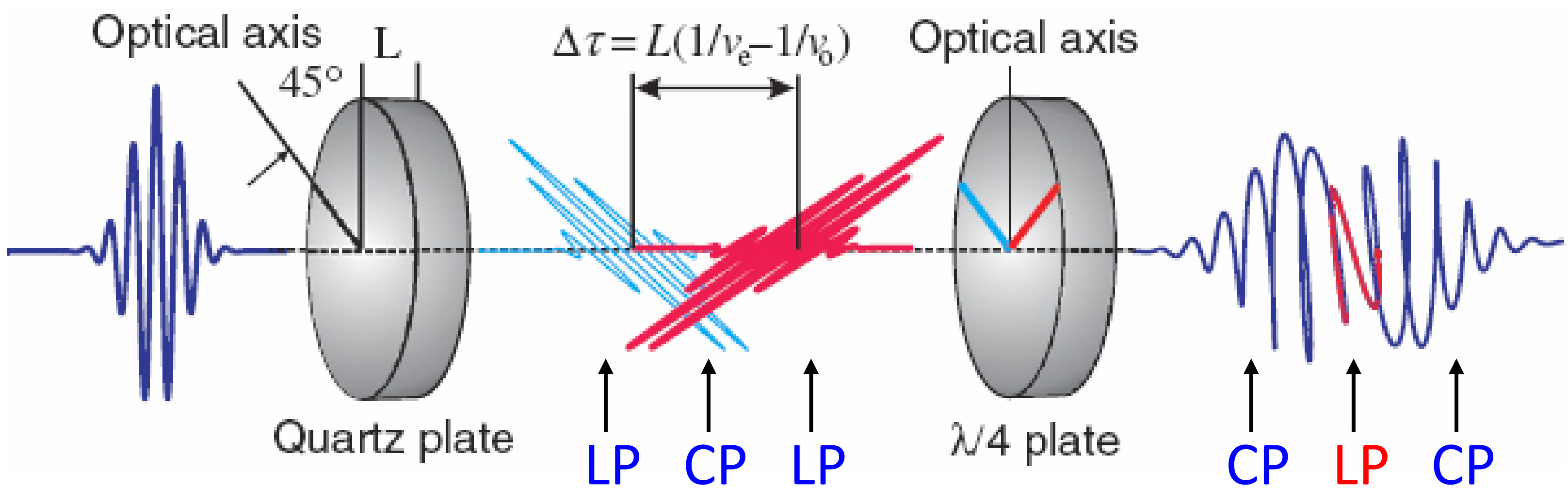
OL, **32**, 3379 (2007); APB, **74**, S133 (2002)



Vectorial pulse with time-varying state of polarization (SOP)

Application of vectorial fs pulse

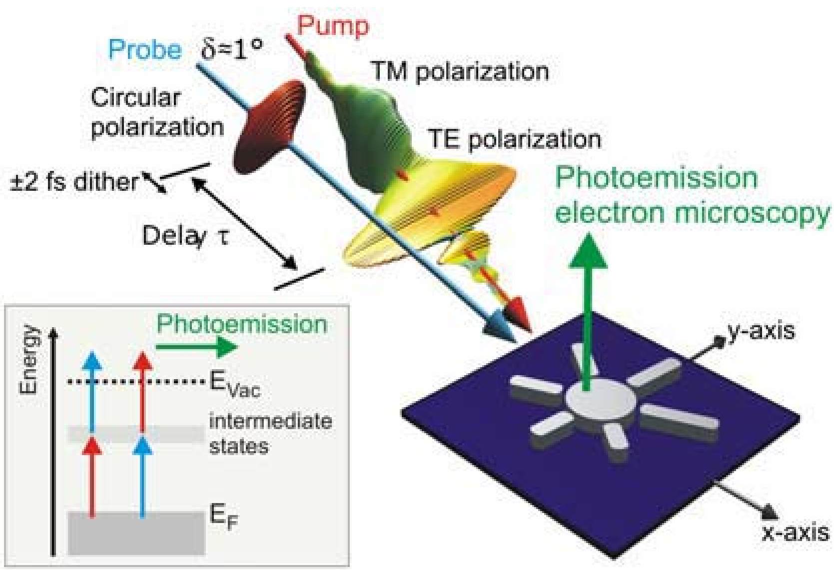
- Linear polarization (LP) transient sandwiched between circular polarization (CP) waveforms ⇒ isolated attosecond pulse generation

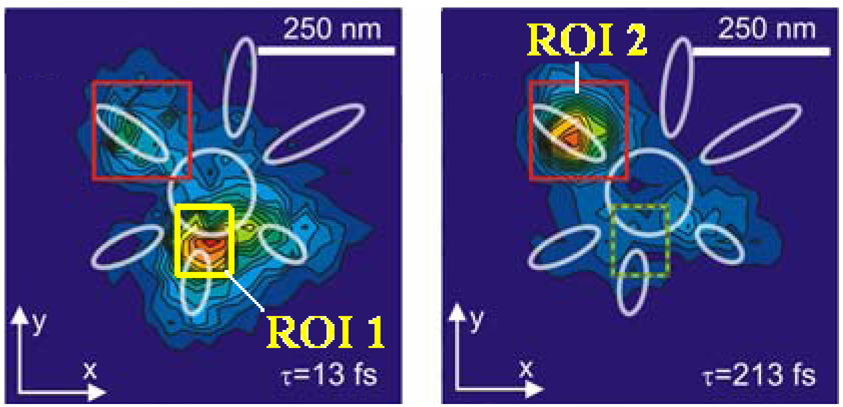


New J. Phys. **10**, 025025 (2008)

Application of vectorial fs pulse

- Selective plasmonic excitation with femtosecond time resolution and nanometer spatial resolution

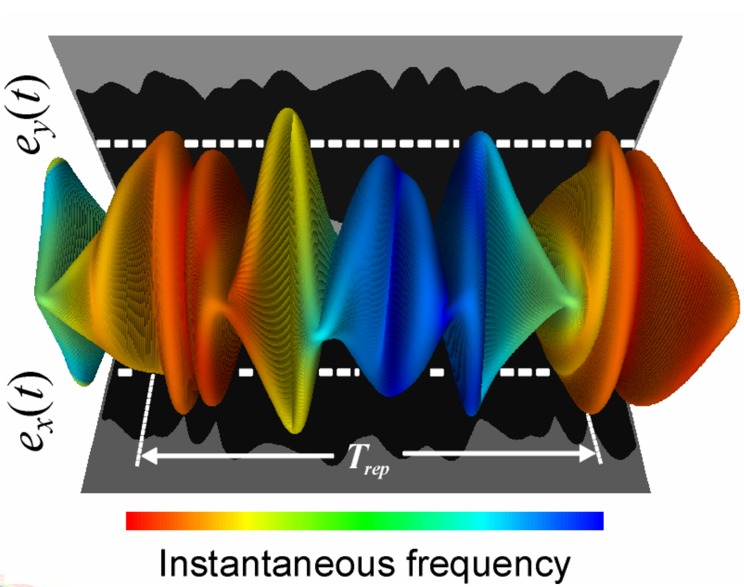


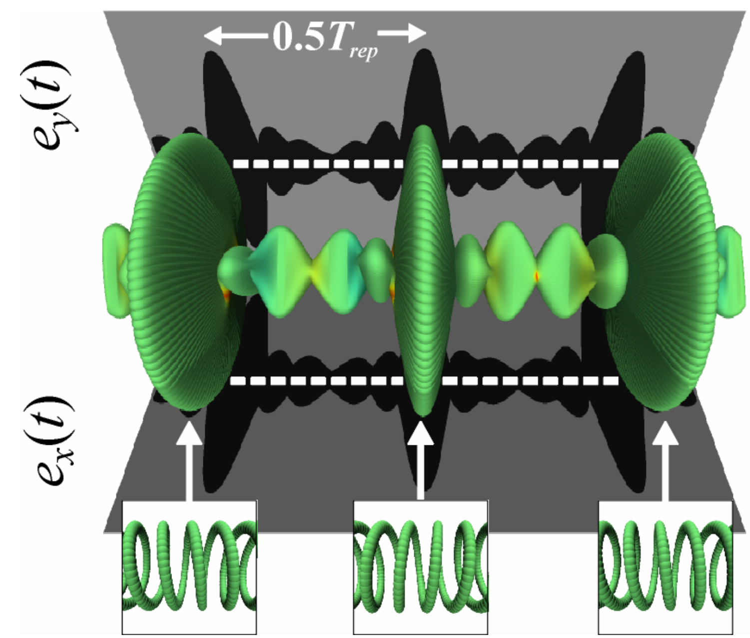


PNAS, **107**, 5329 (2010)

Vectorial OAW (V-OAW)

- (Optical frequency comb) + (polarization LBL pulse shaper) $\rightarrow$ V-OAW
- Waveform can fill the entire time axis
- Intensity repetition rate can be multiplied





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Our goals

- Devise a practically useful method to fully characterize the time evolutions of amplitude, phase, and SOP with fs resolution
- Realize an integrated system for simultaneous measurement and synthesis of V-OAW

Part 2

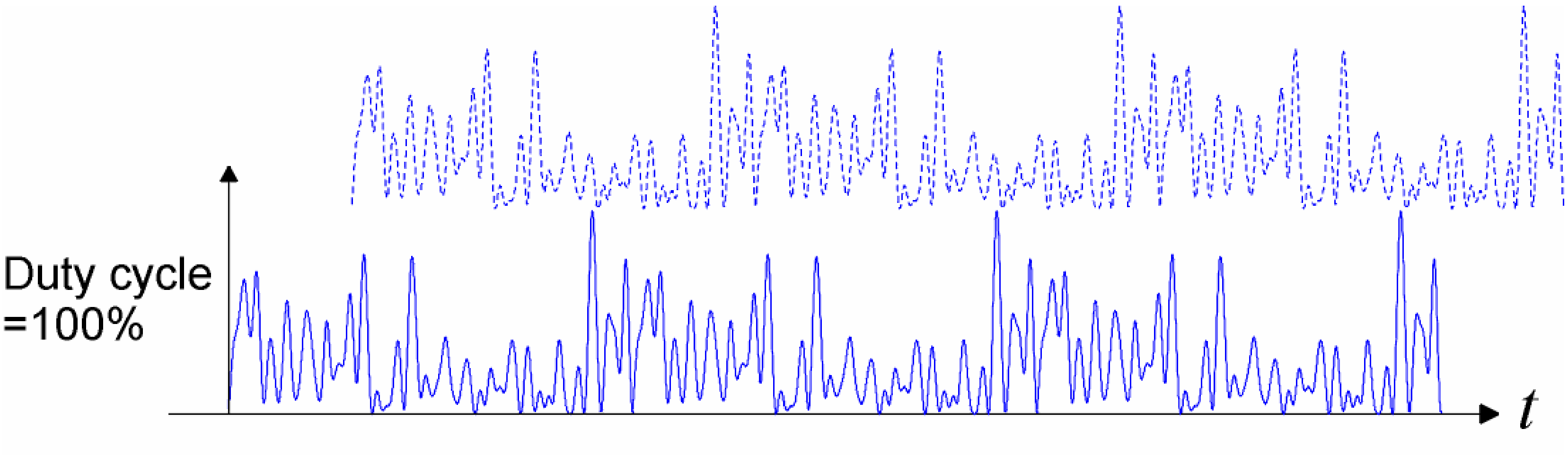
- Background
- Scalar OAW measurement: Orthogonally probed DQ-SSI
- Vectorial OAW measurement: VECTOR
- Conclusions

How to model a scalar OAW?

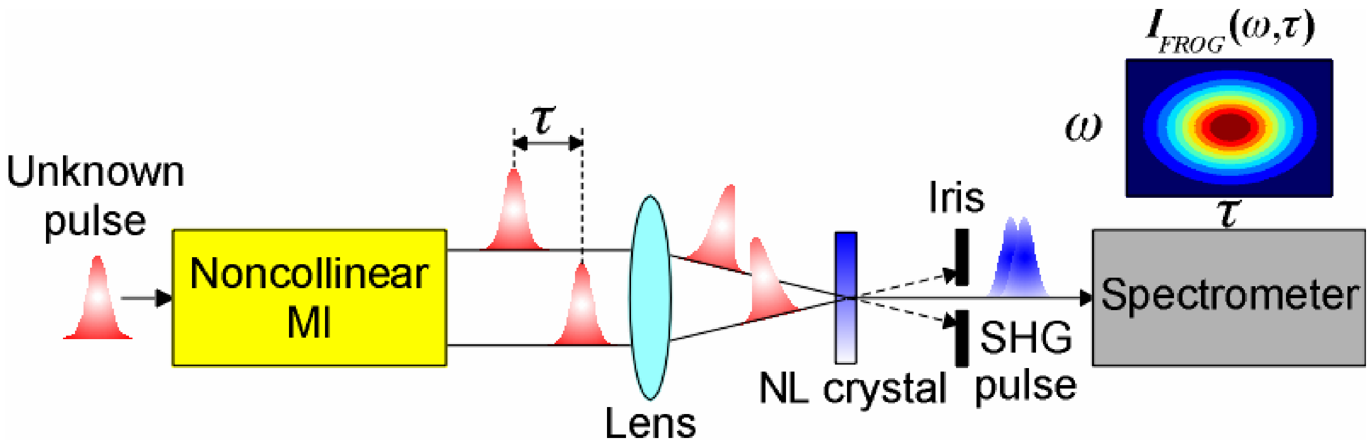
- $A(\omega_n) = |A(\omega_n)| \times \exp[j\phi(\omega_n)]$, $n = 0, \pm 1, \pm 2, \ldots$
- $|A(\omega_n)|$: spectral amplitude, easy to be measured
- $\phi(\omega_n)$: nonlinear component of spectral phase, sufficient to determine the time-domain pulse shape

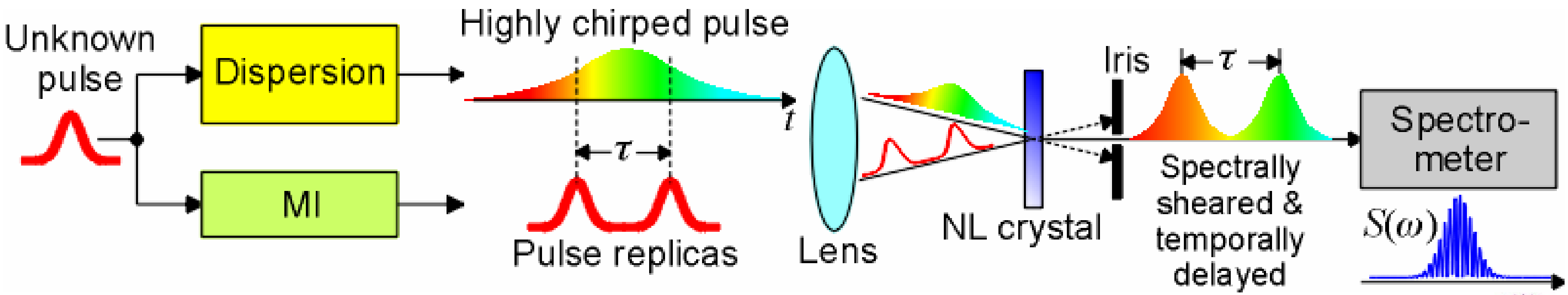
Measuring scalar OAW is difficult

- Cannot create two isolated pulse replicas



FROG, SPIDER do not work!





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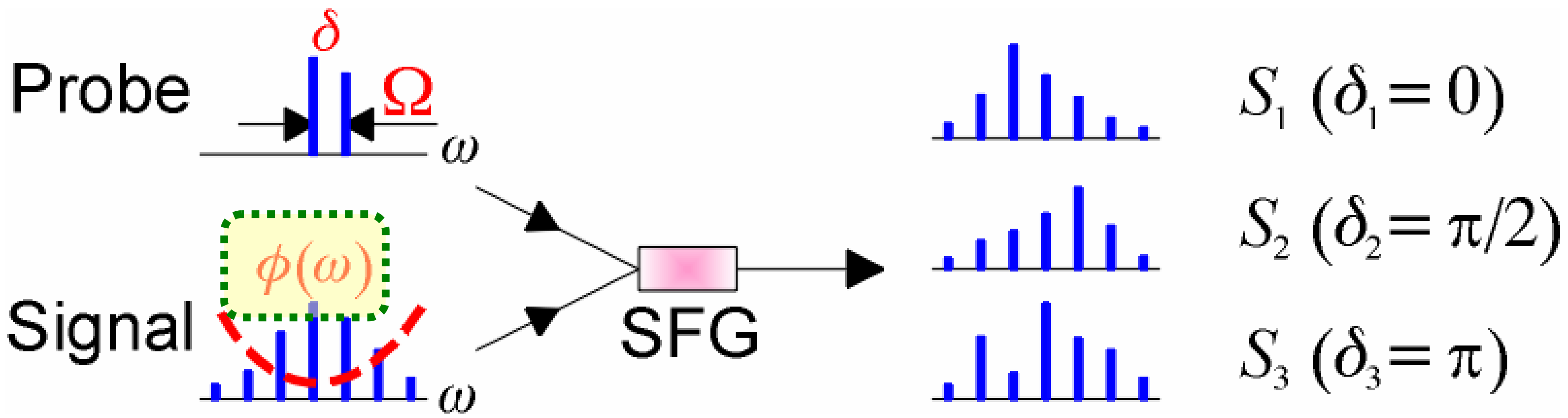
DQ-SSI



- Need a "probe": 2 coherent spectral lines spaced by Ω (spectral shear) and have a controllable relative phase δ
- Signal and probe are mixed for SFG
- Acquire three interferograms $\{S_{1,2,3}\}$ at $\{\delta_{1,2,3}\}$

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Retrieve $\phi(\omega)$ from $S_{1,2,3}(\omega)$

- $S_i(\omega) = B(\omega) + M(\omega)\times\cos[\Delta\phi(\omega)+\delta_i]$ (i = 1, 2, 3),

  where $\Delta\phi(\omega) \equiv \phi(\omega+\Omega) - \phi(\omega)$

Probe phase δ	0	90°	180°
Interferogram	S_1	S_2	S_3
Interferometric term/$M(\omega)$	$\cos[\Delta\phi(\omega)]$	$-\sin[\Delta\phi(\omega)]$	$-\cos[\Delta\phi(\omega)]$

- $B(\omega) = [S_1(\omega) + S_3(\omega)]/2$,
- $\Delta\phi(\omega) = \tan^{-1}[(B-S_2)/(S_1-B)]$,
- $\phi(\omega) = \int\Delta\phi(\omega')d\omega'$

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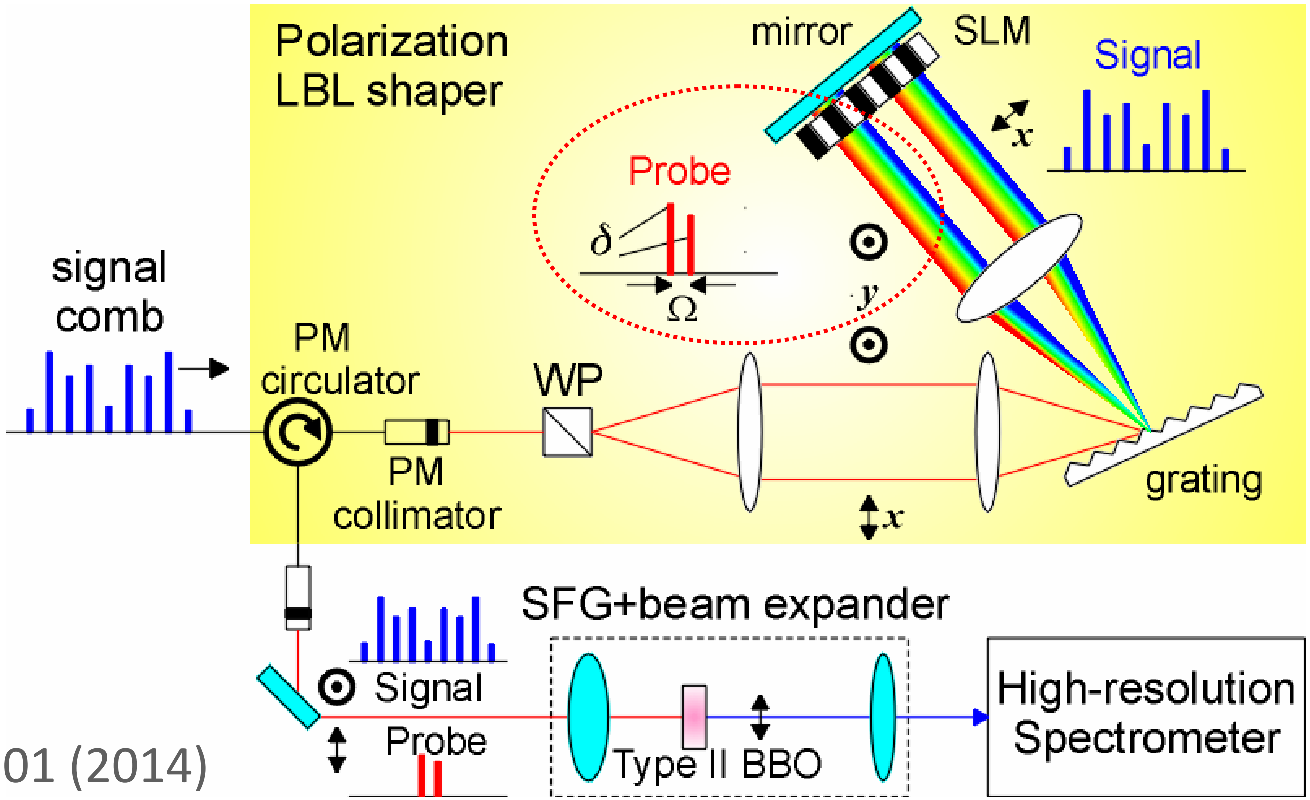
Orthogonally probed DQ-SSI setup



OL, **39**, 1901 (2014)

- All optical, free of optical or RF reference,

  ⇒ can measure Kerr frequency comb (f_{rep} ~ THz)

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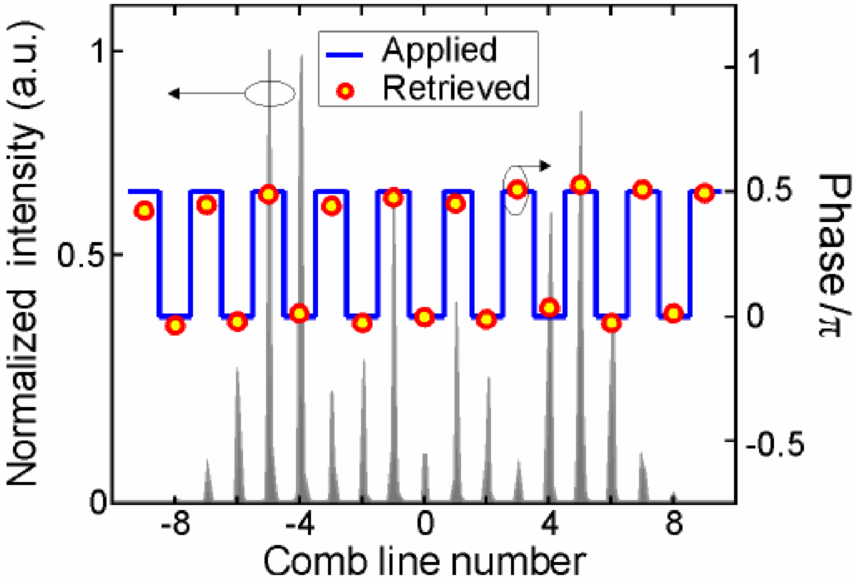
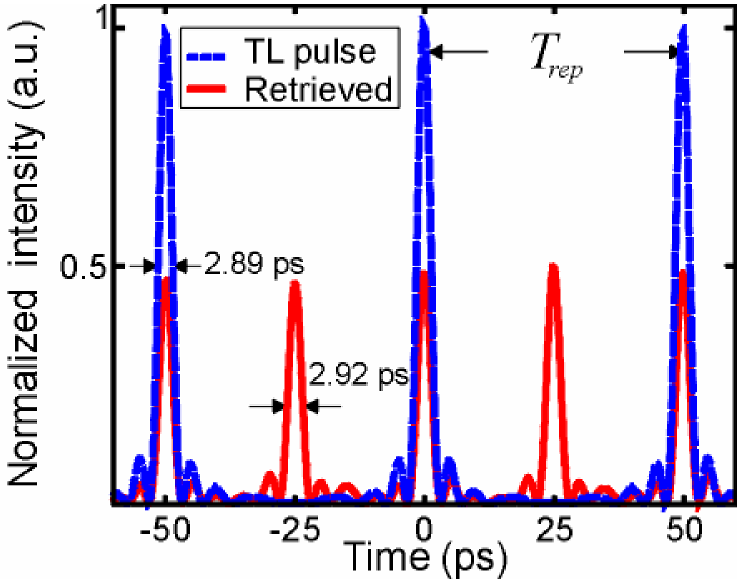
Experiment: Temporal Talbot effect

- Alternating {0,90°} phases are accurately retrieved
- Intensity repetition rate is doubled (20→40 GHz) w/n power penalty





OL, **39**, 1901 (2014)

Part 3

- Background
- Scalar OAW measurement: Orthogonally probed DQ-SSI
- Vectorial OAW measurement: VECTOR
- Conclusions

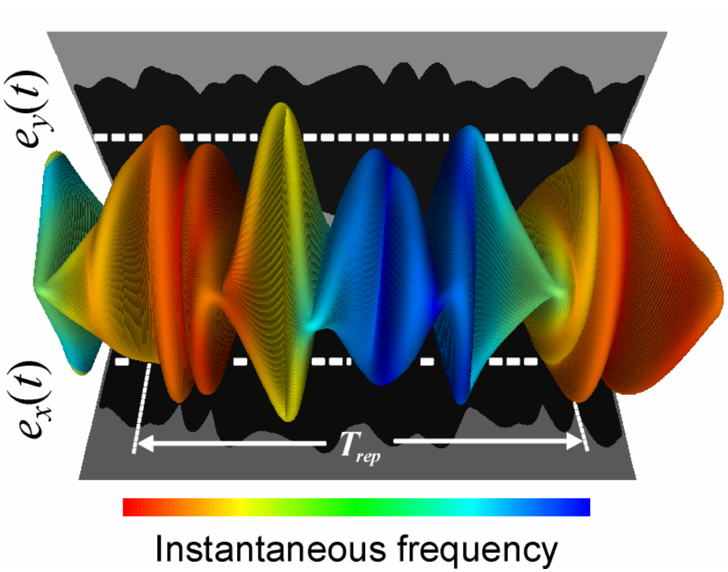
How to model a V-OAW?

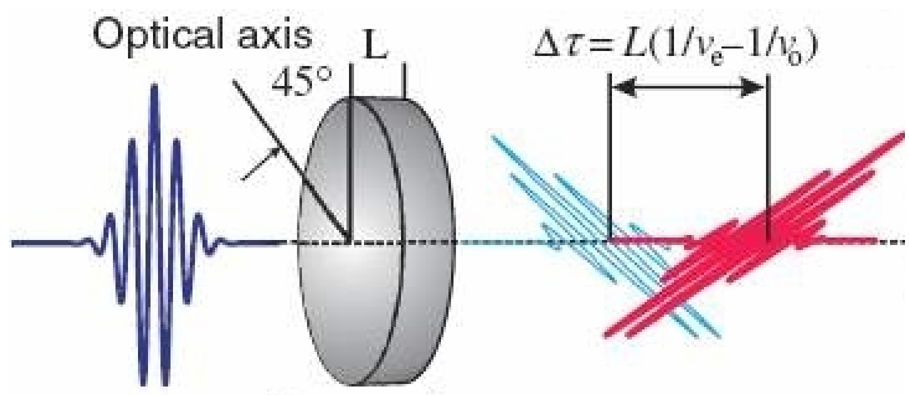
- $\vec{A}(\omega) = \vec{x}|A_x(\omega)|\times\exp[j\phi_x(\omega)] + \vec{y}|A_y|\times\exp[j\phi_y+\tau_{xy}\omega+\theta]$
- $|A_x|$, $|A_y|$: spectral magnitudes
- ϕ_x, ϕ_y: nonlinear components of spectral phase
- τ_{xy}: relative delay between x- and y-polarizations
- θ: relative constant phase between x- and y-polarizations
- The total phase of y-polarization: $\phi_{y,tot} = \phi_y+\tau_{xy}\omega+\theta$

How to determine a V-OAW?

- Measuring the x- and y-polarized pulse shapes is insufficient;

  for τ_{xy} and θ have a profound impact on SOP.

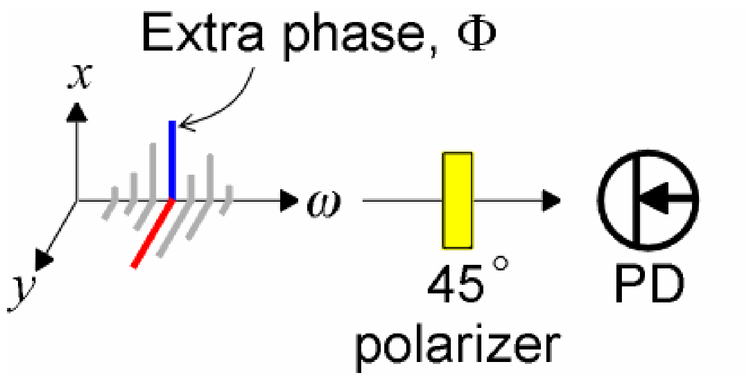


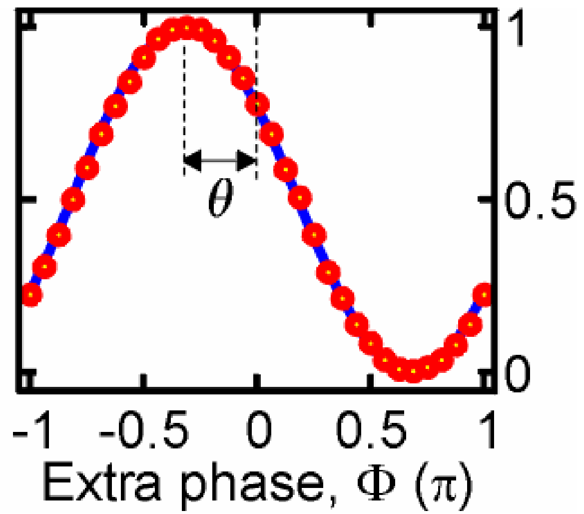


New J. Phys. **10**, 025025 (2008)

4-step method

- Steps 1 & 2: Two scalar OAW measurements $\rightarrow \{\phi_x, \phi_y\}$
- Step 3: Compensate $\phi_{x,y}$, intensity X-correlation $\rightarrow \tau_{xy}$
- Step 4: Single-λ phase-scanning interferometry $\rightarrow \theta$

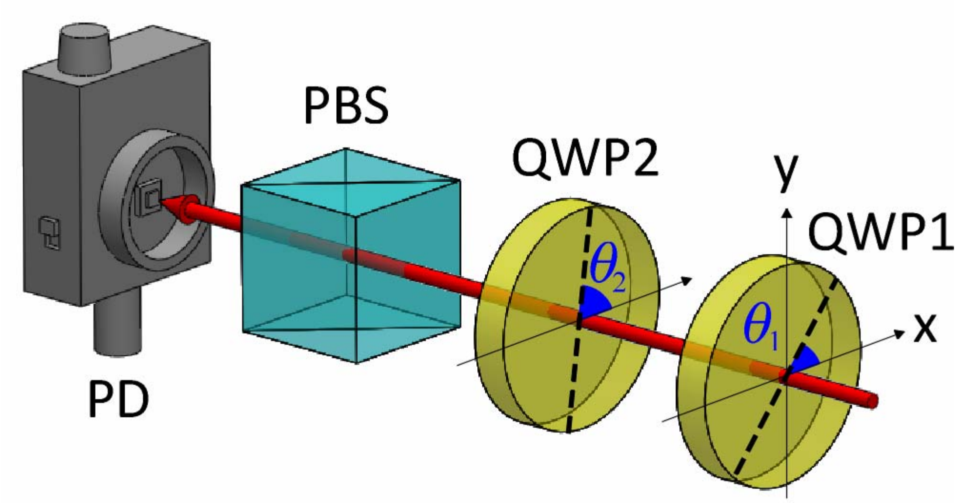




- Cons: complicated, need interferometric stability

OE, **20**, 27062 (2012)

Single-λ polarimeter



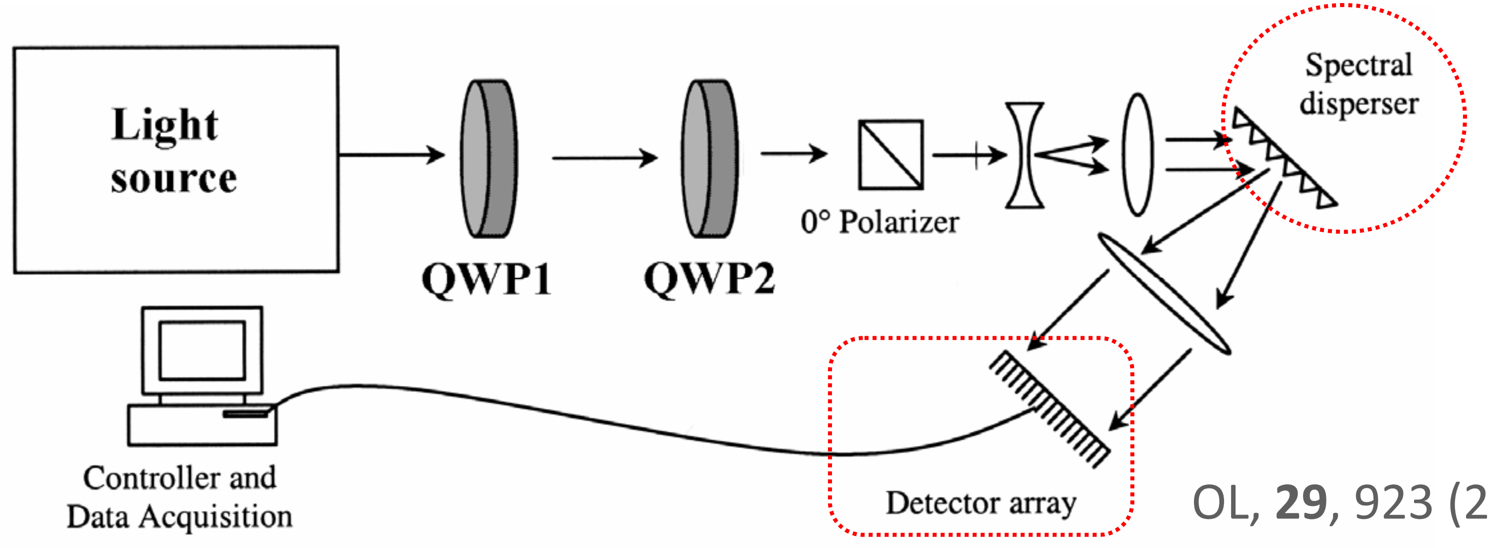
θ_1	θ_2	Power
90°	0°	I_0
90°	-45°	I_{45}
-45°	-45°	I_{90}
-45°	0°	I_{RHC}

- The Stokes vector is

$$\mathbf{S}=\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}=\begin{bmatrix} I_0+I_{90} \\ I_0-I_{90} \\ 2I_{45}-S_0 \\ 2I_{RHC}-S_0 \end{bmatrix}=\begin{bmatrix} I_x+I_y \\ I_x-I_y \\ 2I_xI_y\cos\Delta\phi_{xy} \\ 2I_xI_y\sin\Delta\phi_{xy} \end{bmatrix}$$

λ-parallel polarimeter (WPP)

- Add a spectral disperser and a PD array …



OL, **29**, 923 (2004)

- In this case, one can get $\{I_x(\omega), I_y(\omega), \Delta\phi_{xy}(\omega)\}$, where

$I_{x,y}(\omega) = |A_{x,y}(\omega)|^2$, $\Delta\phi_{xy}(\omega) = \phi_{y,tot}(\omega) - \phi_x(\omega)$

↓ DQ-SSI

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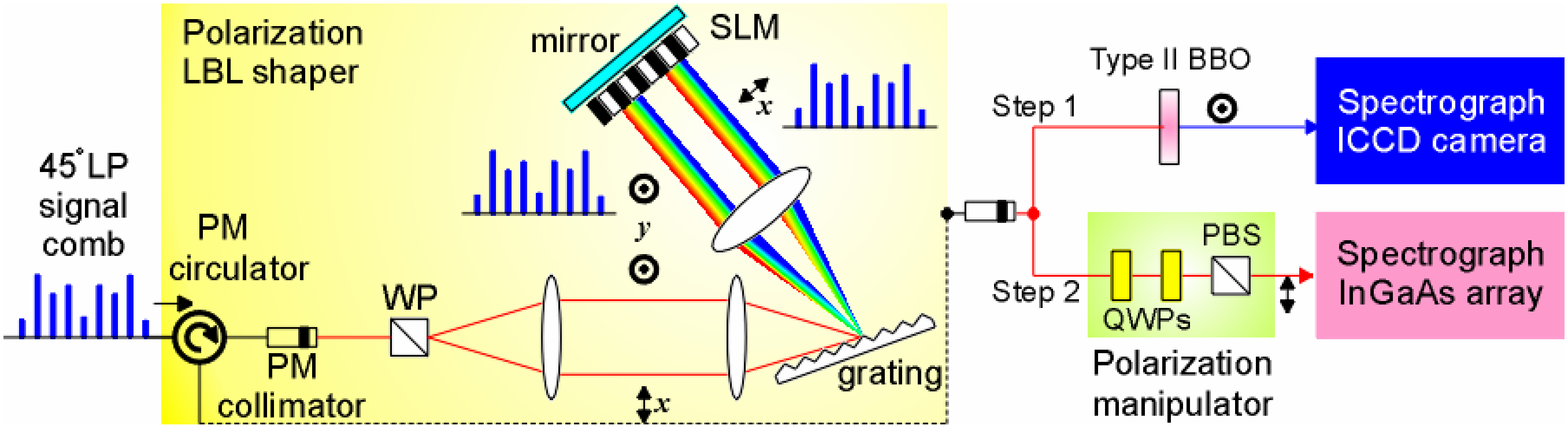
VECTOR method

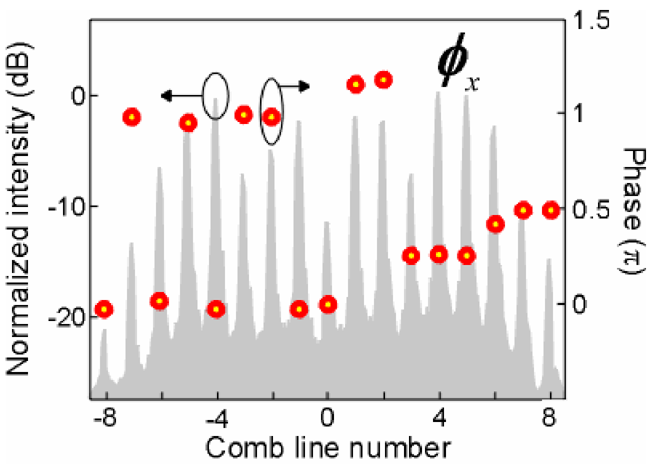


- Step 1 (DQ-SSI): Acquire $\{S_{1,2,3}(\omega)\}$, $\rightarrow \phi_x(\omega)$, $\rightarrow$ the x-polarized OAW.
- Step 2 (WPP): Acquire $\{I_{0,45,90,RHC}(\omega)\}$, $\rightarrow \Delta\phi_{xy}(\omega)$, $\rightarrow$ $\phi_{y,tot}(\omega)$, $\rightarrow$ the y-polarized OAW, and τ_{xy}, θ.

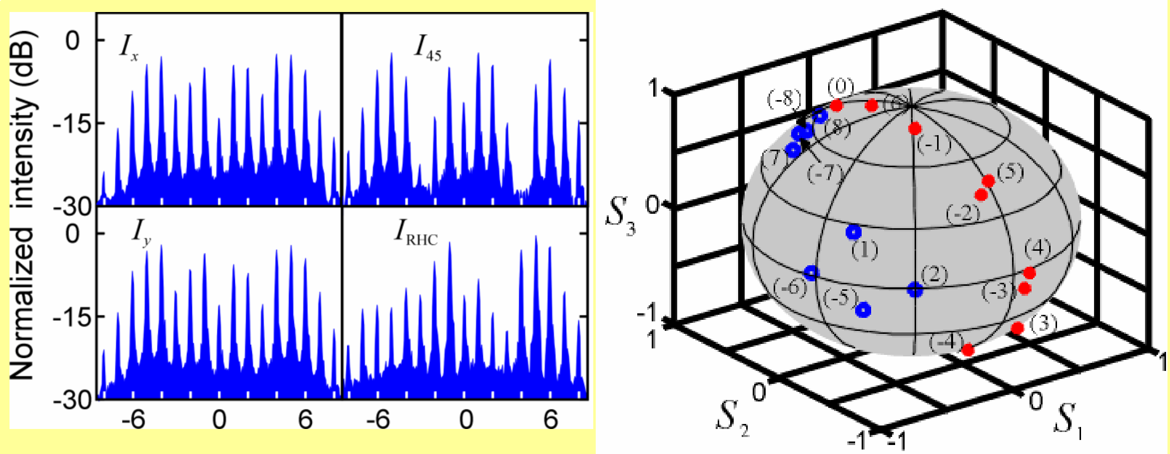
OE, **22**, 28838 (2014)

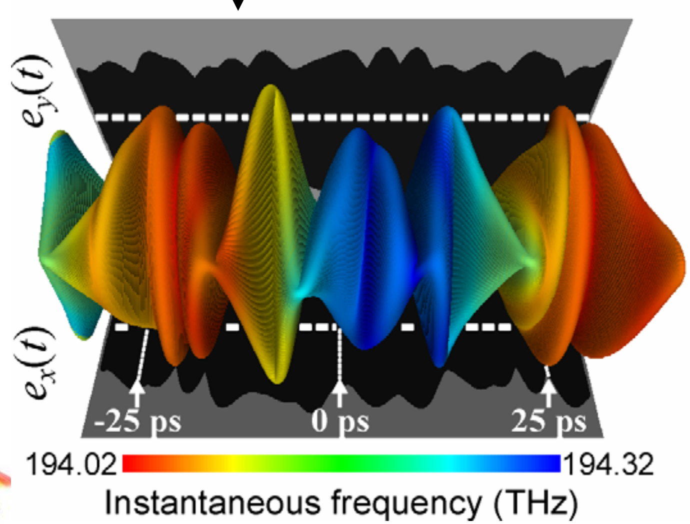
Experiment: 100% duty cycle

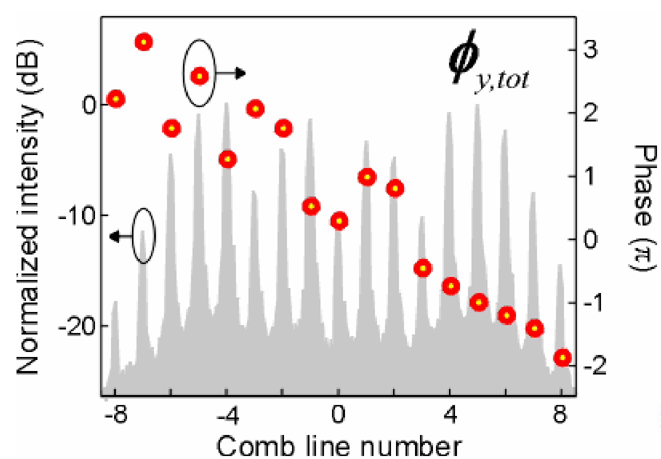
Step 1: DQ-SSI



Step 2: WPP







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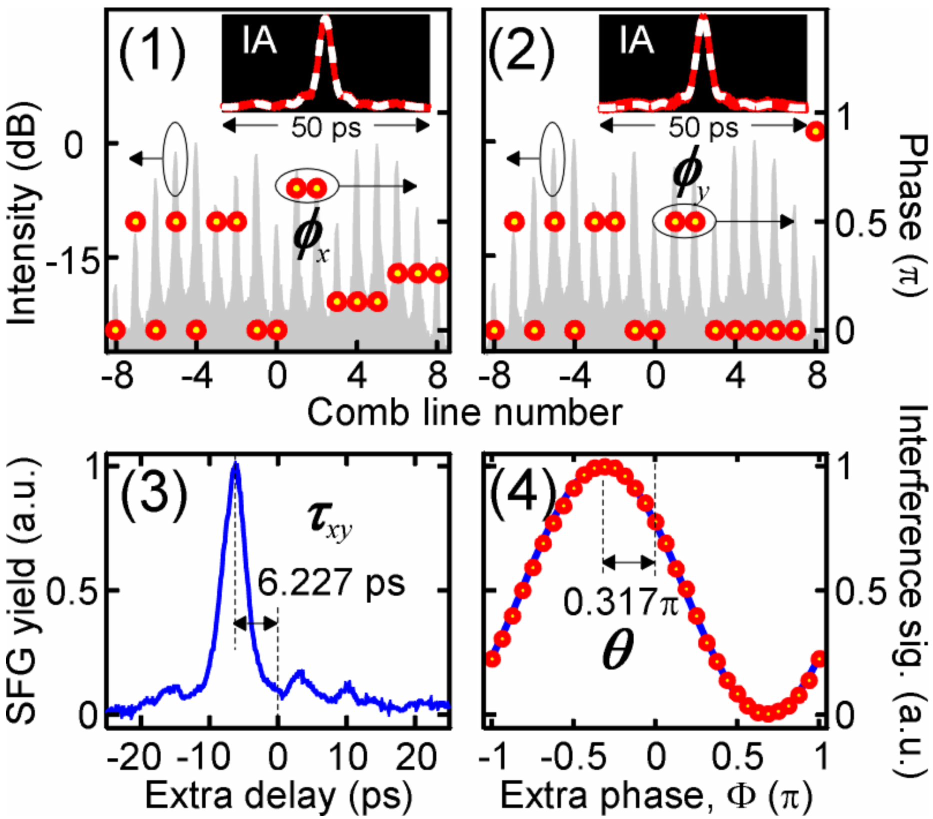
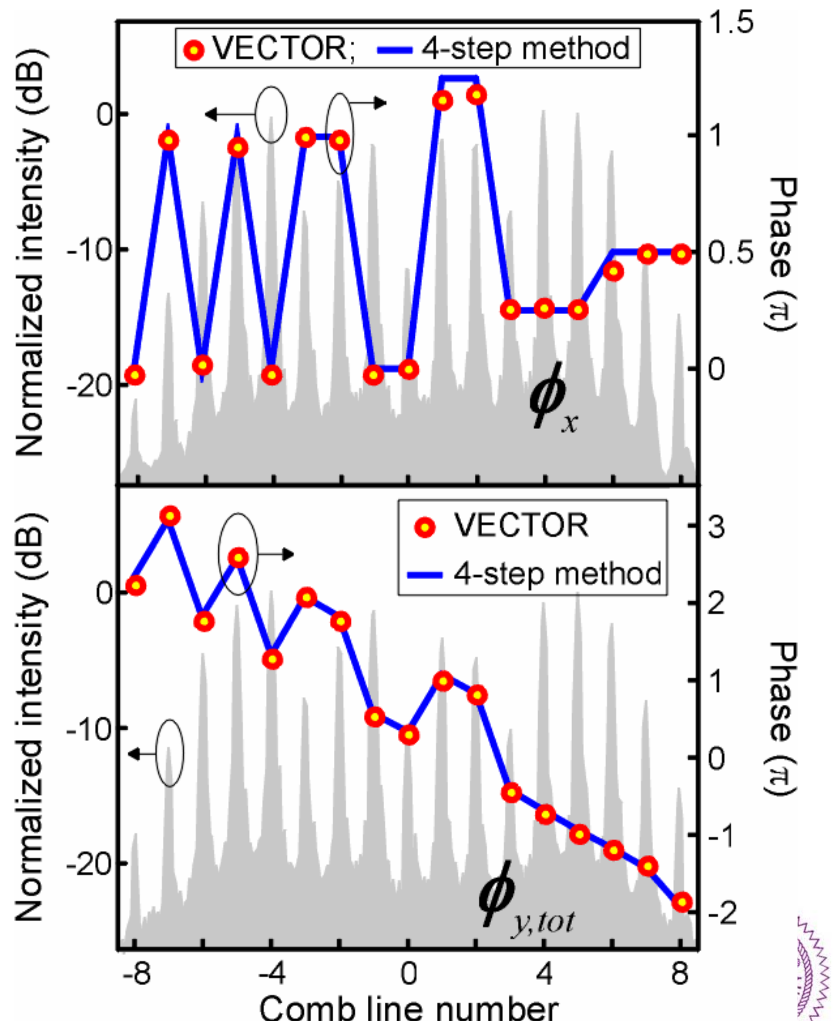
Verification of VECTOR accuracy

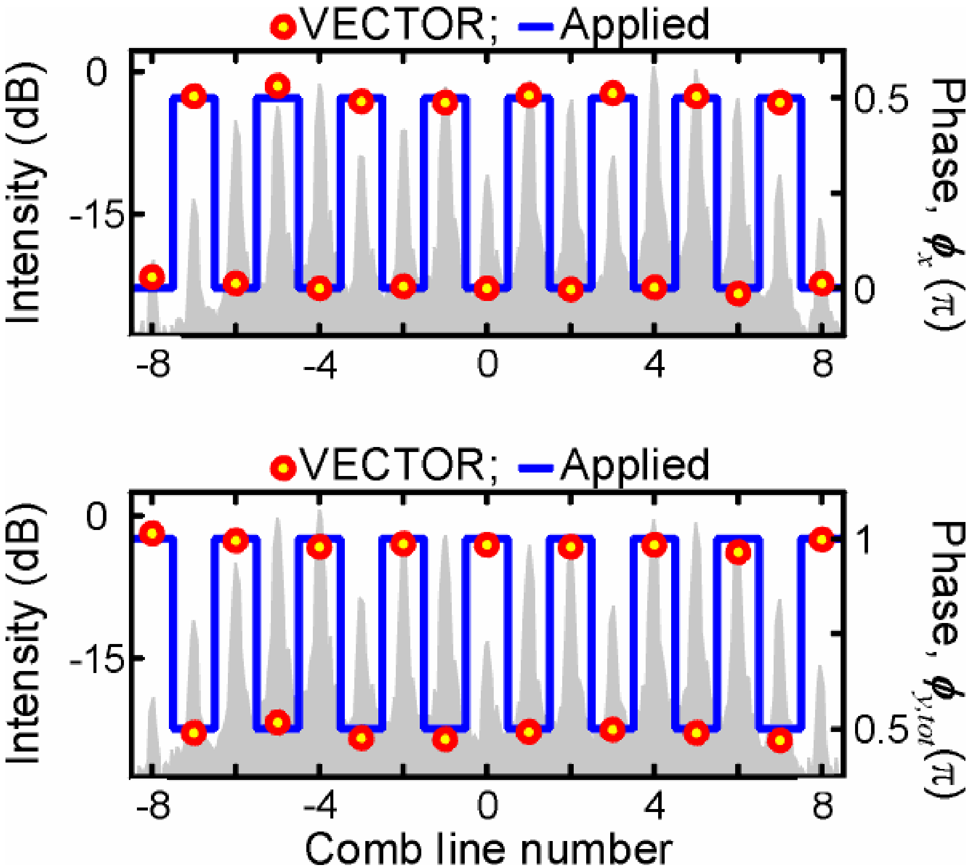
- 4-step method result

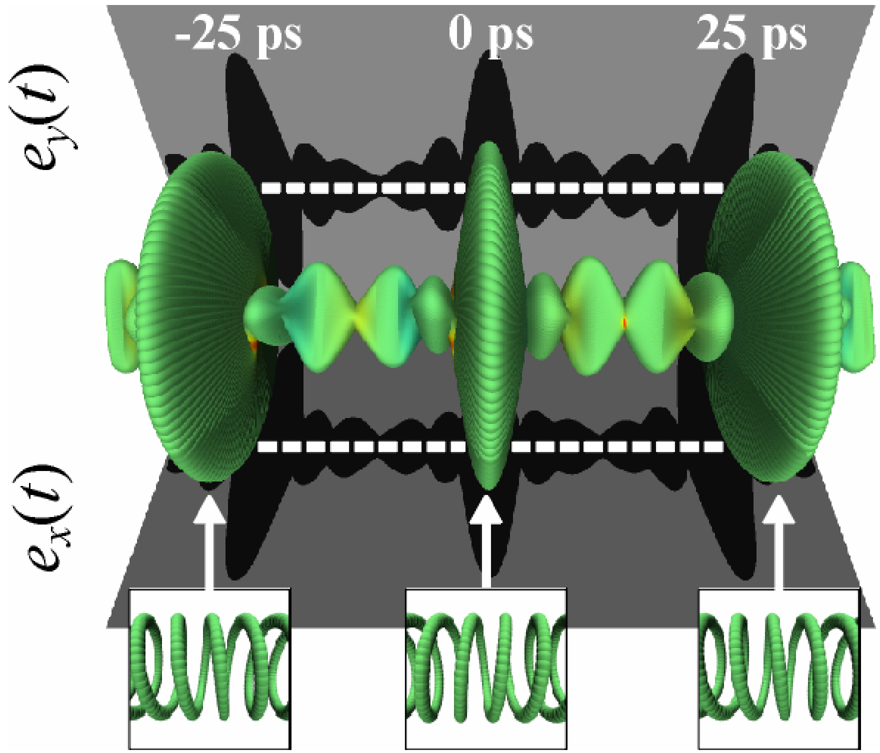


- VECTOR vs. 4-step



Experiment: Temporal Talbot effect





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Conclusions

- VECTOR is

1. OAW compatible (no need of isolated pulse replicas)
2. Free of optical or RF reference, $\Rightarrow$ applicable to Kerr frequency comb of high (>100 GHz) repetition rate
3. Non-iterative
4. Non-ambiguous
5. Robust against interferometric perturbation
6. Integrated system for measurement and synthesis