Coherent OAM Modulation Technique using Versatile Phase Controllability of Multi-optical-combs towards Sensitive and Rapid Spatiotemporal Spectroscopy

Akifumi Asahara[1], Ruichen Zhu[1], and Kaoru Minoshima[1]
[1]*Department of Engineering Science, Graduate School of Informatics and Engineering, The University of Electro-Communications (UEC), 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan*
aki.asahara@uec.ac.jp, k.minoshima@uec.ac.jp

Abstract: A new orbital angular momentum (OAM) modulation method is demonstrated based on the high phase controllability of multi-optical-combs. The developed method will lead to sensitive and rapid spatiotemporal spectroscopy using optical frequency combs. © 2022 The Author(s)

1. Introduction

Dual-comb spectroscopy (DCS) is one of promising applications of optical frequency combs, because it enables unprecedentedly high acquisition speed with excellent precision over a broadband spectral range [1]. Although this method has been developed mainly in the field of molecular precision spectroscopy, progress has been made across various expanding applications, such as multidimensional spectroscopy [2] and ultra-high sensitivity detection [3]. As one of new applicability of DCS, we have recently been promoting a unique DCS technology extended towards optical vortex researches [4,5]. Optical vortex is a light with a spiral phase distribution and has attracted attention in fields such as spatial multiplexing communication and super-resolution imaging. The optical helicity is determined by the topological charge ℓ of the Laguerre–Gaussian beam. The ℓ parameter is also called as orbital angular momentum (OAM) mode number because optical vortex transfers OAM of light. In our previous reports, we demonstrated detailed spatiotemporal characterization method using single-pixel DCS imaging technique [4]. The strong advantage of our developed method is the multidimensional detectability of a plenty of spectroscopic information by evaluating the real and imaginary parts of the transverse (OAM spectrum) and longitudinal (Optical frequency spectrum) modes of light at the same time. This way, the DCS is extended to the transverse dimension far beyond the conventional application range.

Here, we propose a novel OAM modulation method utilizing the high coherent controllability of multi-optical-comb pulses. The principle of the proposed method is based on our recently developed polarization-modulated DCS technique [6] (Fig. 1). The optical comb is coherently controlled through the frequency parameters, the repetition rate f_{rep}, carrier-envelope offset frequency f_{ceo}, and their difference in DCS, Δf_{rep} and Δf_{ceo}. The Δf_{rep} defines the acquisition rate of the interferogram (IGM) in DCS, and Δf_{ceo} determines the IGM-to-IGM evolution of the carrier-envelope phase (CEP). With a condition of $\Delta f_{\mathrm{ceo}} = \Delta f_{\mathrm{rep}}/2$, π-rad phase switching is induced to the adjacent IGMs, and this feature can be utilized to circular polarization switching using dual-comb. In the present paper, by optically converting the circular polarization into OAM state, we demonstrate a proof-of-principle experiment on the coherent OAM switching. The coherent control using the multi-comb system enables a rapid, precise, and arbitrary OAM modulation. Such an advanced OAM modulation technique has a great potential for highly sensitive and rapid spatiotemporal DCS, that is useful for OAM dependent dichroism of chiral materials, dynamical OAM dependent phenomena, and *etc*.

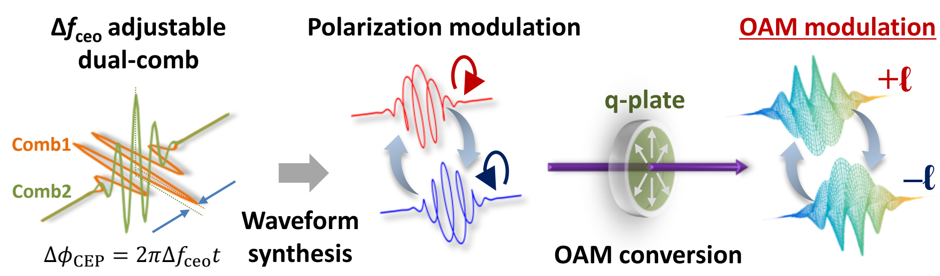

Fig. 1: Proposed concept of coherent OAM modulation technique using phase controllability of multi-optical-combs.

2. Experiment and Results: Coherent OAM Modulation using Multi-optical-combs

Figure 2(a) illustrates the experimental system. An Er fiber comb (Signal comb) was used as an optical comb source. The output was incident to an acousto-optic modulator (AOM) and was split into 0$^{\mathrm{th}}$ transmitted and 1$^{\mathrm{st}}$ diffracted beams. The f_{ceo} of the diffracted comb was shifted according to f_{AOM} induced on the AOM, and these two combs were treated as an effective dual-comb with an adjustable Δf_{ceo}. The combs were superposed with a cross-polarization state on a polarizing beamsplitter. Temporal overlap was adjusted using a piezo delay line, and the polarization-modulated comb pulses were generated as a synthetic optical waveform. Next, we generated OAM-modulated comb pulses using a q-plate, which is a well-known optical component that converts circular polarized light into optical vortex. Here, we used a q-plate that can generate $\ell = +1$ or -1

vortex light depending on the right or left circular polarization. Hence, coherent OAM modulation between $\ell = +1$ and -1 is realized using optical comb.

To validate the OAM modulation, we performed DCS experiment using another tightly phase-locked Er comb with Δf_{rep} (Local comb). First, the generated OAM-modulated pulses were split into two optical paths with different optical length. In each path, a quarter-waveplate was inserted with different optical axis of ±45 deg. After overlapping the two optical paths coaxially, another q-plate was inserted, and the output was coupled into a single-mode fiber. The light was interfered with the local comb at a fiber coupler, the IGM signal was obtained using an InGaAs detector and 100-MHz digitizer. Thanks to this experimental design, the optical vortex pulses with $\ell = +1$ or -1 can be converted into the fundamental mode ($\ell = 0$) when the light goes through the upper or lower optical path. Because only the $\ell = 0$ mode is coupled into the single-mode fiber, the dynamical OAM mode evolution can be characterized from the IGM intensity. In the experiment, the f_{rep} was ~56.6 MHz, the Δf_{rep} was ~1022 Hz, the f_{ceo} was 21.4 MHz, and the Δf_{ceo} was set to ~511 Hz to fulfill the π-rad phase switching condition of $\Delta f_{ceo} = \Delta f_{rep}/2$.

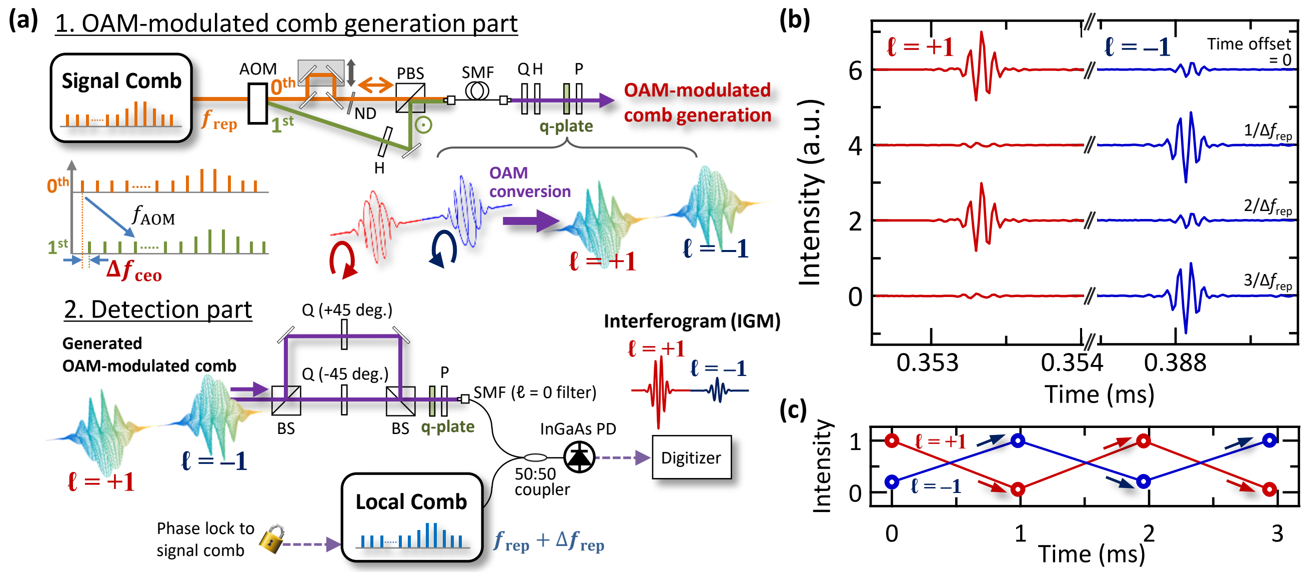

Fig. 2: (a) Experimental setup for verification of coherent OAM-modulation using multi-optical-combs. Q: quarter-waveplate, H: half-waveplate, P: polarizer, ND: neutral density filter, SMF: single-mode fiber, PD: photodetector. (b) Result of obtained IGMs. Intensity was normalized by the peak value. (c) IGM intensity evolution showing OAM switching.

The result of obtained IGMs are illustrated in Fig. 2(b). The red (blue) IGM corresponds to the OAM state of $\ell = +1$ (-1), respectively. The four IGM pairs with an acquisition rate of Δf_{rep} are summarized, and the periodical IGM change is observed. In Fig. 2(c), the evolution of the IGM intensity is plotted. The extinction ratios were 0.06 and 0.20 for $\ell = +1$ and -1 switching. Consistent with the proposed theory, OAM switching modulation with Δf_{rep} rate was obtained with the clear contrast. Hence, the comb-based coherent OAM modulation was successfully verified.

3. Conclusion

We demonstrated the coherent OAM modulation technique based on the versatile phase controllability of multi-optical-combs. The developed method will be utilized, for example, for an advanced OAM-modulated lock-in measurement in studies on OAM dependent dichroism in chiral or magnetic materials and for dynamic OAM-related phenomena. This method will pave the way for highly sensitive, rapid, broadband, and arbitrary spatiotemporal spectroscopy using the full potential of optical frequency combs.

This research was supported by MEXT/JSPS KAKENHI Grant Number 21H01840 and 21H05014.

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