# Continuous Synthesis of Arbitrary Optical Waveforms Through Manipulation of Highly Discrete Spectra

(Abstract)

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In the development of ultrafast laser technologies, the concept of arbitrary optical waveform generation (AOWG) emerged. This concept can be regarded as an optical analogue of function generators or pulse generators in electronics. The AOWG technology is expected to provide user-demanded optical waveforms for various purposes, and thus, important in the context of light-matter interaction studies and the future informatics. After the invention of optical frequency comb, ultrafast lasers acquired accessibility to electromagnetic waves, which had a huge impact on light-matter interaction studies and opened up a new frontier: lightwave electronics. Several researchers discussed an apparently similar but fundamentally different idea: AOWG through manipulation of highly discrete spectra. The idea is expected to enable continuous generation of non-sinusoidal electromagnetic fields. However, experimental realization is yet to be seen. The purpose of this thesis is threefold: firstly, to provide details of the development of an AOWG system based on the idea of manipulation of highly discrete spectra, secondly, to provide a method to manipulate the polarization of highly discrete spectra, and thirdly, to provide a prospect for applications of these technologies in the field of lightwave electronics. The thesis consists of four parts. The synopsis of each part is given below.

In Part I, we review the developement of the ultrafast laser technologies and the technologies related to AOWG. We pick up several important researches in these areas of study. We also see that the development of laser technologies and nanodevices is opening up a field of lightwave electronics.

In Part II, we provides the development of AOWG system based on the concept of manipulation of highly discrete spectra. Here, we give the synopsis of our methodology. The two continuous wave source, $\omega_2$ (1200 nm) and $\omega_3$ (800 nm), were generated by two independent external-cavity diode lasers. The difference frequency $\omega_1$ (2400 nm) was generated by the nonlinear frequency conversion. The three frequency modes were phase-locked by using the optical frequency division technique. The higher modes, $\omega_4$ (600 nm) and $\omega_5$ (480 nm), were also generated by the nonlinear conversion. The optical frequency division technique makes sure that the five frequencies have integer-ratio relationship, i.e., $\omega_1 : \omega_2 : \omega_3 : \omega_4 : \omega_5 = 1\omega : 2\omega : 3\omega : 4\omega : 5\omega$. Nextly, the spectral amplitude and phase of the five modes were manipulated in an arbitrary manner. The generated waveform was incident on a barium borate crystal or a lithium niobate crystal to generate the higher modes, $6\omega$ and $7\omega$, or $4\omega$, respectively. By using these $4\omega$, $6\omega$, and $7\omega$, the spectral interferometry was conducted to determine the waveform. Experimental results suggested that the different

kinds of pulse trains and a sawtooth waveform were generated in a continuous manner. The developed system was also examined for the reproducibility of the waveform generation.

In Part III, we provide theoretical and numerical analyses of a method to manipulate the polarization of highly discrete spectra. A system of two variable-thickness waveplates were analyzed by using Jones matrices. It was numerically shown that this system is able to manipulate the polarization of highly discrete spectra such as shown in Part I: eight different targets were shown to be achieved by this method with an error tolerance of approximately 10 %. This result means that the method can be used to generate an arbitrary polarization in a temporal domain. The method was also examined from various aspects, including the dependence on a target, or the number of the controllable frequency modes. The characteristics of the method was elucidated by a simple model based on the distributions of errors on the Poincare sphere. Furthermore, the experimental implementation of the method was discussed. The Jones matrices of the two variable-thickness waveplates were extended to two pairs of wedged waveplates, including Fresnel's reflection and the beam path discrepancy due to the refraction. It was shown that, in the presence of these undesirable effects, the arbitrariness of the manipulation is not spoiled.

In Part IV, we numerically examined the possibility of manipulating tunneling currents at a nanogap structure on a substrate by using waveforms generated by the AOWG system shown in Part I. The well-known Simmons model was used to estimate the averaged current in the presence of ultrafast optical waveforms. The effects of heat caused by light absorption by a substrate was also estimated. The numerical estimation showed that the tunneling currents could show the dependence on optical waveforms and the difference of the current could be in a detectable level. Even though the discussions provided in this part were rather simple, it gave us a good starting point towards an actual application of our AOWG system to nanodevices and the lightwave electronics.

In conclusion, we first showed the experimental demonstration of the generation of arbitrary optical waveforms in a continuous regime by using highly discrete spectra. The principles of operation and the experimental methodology were provided in detail. Nextly, a method for manipulating the polarization of highly discrete spectra was discussed. Lastly, we showed the possibility of applying the AOWG system to device applications by providing numerical estimations of tunneling currents manipulated by optical waveforms. In this way, the thesis provides sufficient information and discussions about the new AOWG system and its future application in device technologies.

## Publications related to thesis

### Articles

1. **Tomura, A.**, Nomura, M, Ohae, C., & Katsuragawa, M., Generating arbitrary polarization states by manipulating thicknesses of a pair of uniaxial birefringent plates, *Physical Review A*, 109, 023535 (2024).
   https://doi.org/10.1103/PhysRevA.109.023535

### Proceedings

1. **Tomura, A.**, Ohae, C., Nakagawa, K., Minoshima, K., & Katsuragawa, M., Continuous Synthesis of Arbitrary Optical Waveforms on a Sub-Femtosecond Timescale. *Proceedings of the 2022 Conference on Lasers and Electro-Optics Pacific Rim*, CWP2E_01, (2022).
   https://doi.org/10.1364/CLEOPR.2022.CWP2E_01

2. **Tomura, A.**, Ohae, C., Minoshima, K., & Katsuragawa, M., Ultrahigh-Repetition-Rate Half-Cycle Pulse Synthesizer Operating at 125 THz. *Frontiers in Optics + Laser Science* APS/DLS, JTu4A.121, (2019).
   https://doi.org/10.1364/FIO.2019.JTu4A.121