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科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　４ 年　 ５ 月 １３ 日現在

機関番号：８２４０１
研究種目：若手研究
研究期間：2020～2021
課題番号：２０Ｋ１５１９７

研究課題名（和文）Development of ultrabroadband optical vortex source

研究課題名（英文）Development of ultrabroadband optical vortex source

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交付決定額（研究期間全体）：（直接経費）　　3,200,000円

研究成果の概要（和文）：　様々な波長範囲での光渦の応用に対して高まる需要を満たすために，本研究の目的は，900ナノメートルから2400ナノメートルまで連続的に及ぶ波長範囲を持つキャリア包絡線位相制御可能な超広帯域の光渦の開発を目指す。 私の知る限り，この光源は，光渦のこのような広いスペクトル範囲を初めて実現したものである。 光源を実行するために，本研究を2つの部分に分割した。（1）まず，パルスのキャリア包絡線位相を定量的かつ任意に制御するために，キャリア包絡線位相制御可能のアルゴリズムを開発した。（2）2つ目は，超広帯域渦パルスを生成するシステムを開発した。

研究成果の学術的意義や社会的意義
The more than a century old Sagnac interferometer is put to first of its kind use to generate optical vortex with more than an octave bandwidth. This combination leads to a high quality vortex pulse than ever reported literatures.

研究成果の概要（英文）：In order to meet an increasing demand for applications of optical vortices with a variety of wavelength ranges, this research successfully realized the development of a table-top achromatic (multi-color) vortex source with wavelength range continuously spanning from 2400 nm to 900 nm (short-wave infrared, SWIR).
During this period, I also developed a technique for controlling the carrier-envelope phase (CEP) of single-cycle pulses (Opt. Express, 30, 10818, 2022) and this technique was further combined with the generation of the broadband vortex source in the SWIR region. A CEP controllable, over-octave bandwidth, SWIR vortex source was successfully generated. This light source is expected to provide new applications and ideas in the fields of singular and ultrafast optics.

研究分野：光工学および光量子科学関連

キーワード：singular optics　ultrafast optics　laser technology

１．研究開始当初の背景

In previous studies, I mainly focused on the investigation in optical vortex sources of a narrow bandwidth in the near infrared (NIR) regime. To generate such an optical vortex, the general way is to transform a TEM_{00} Gaussian beam through a mode converter. To extend the same knowledge to generate an ultrabroadband vortex source as proposed in this project, one need to overcome the undesirable dispersion may occur in the optical elements. In addition, it is not easy to prepare a strong ultrabroadband TEM_{00} Gaussian source for the mode conversion into an optical vortex. These challenges greatly increase the difficulty in the realization of an ultrabroadband vortex. As a result, so far there is no such a vortex source whose spectrum range can continuously span an over-octave bandwidth with a controllable carrier-envelope phase (CEP). Such an optical vortex source will be useful not only for applications of various wavelengths but also for studies in optical manipulations using optical vortices.

２．研究の目的

In order to meet an increasing demand for applications of optical vortices in a variety of wavelength range, this research aims ***(Goal)*** <u>to build up a CEP controllable achromatic (multi-color) vortex source with wavelength range continuously spanning from 900 nm to 2400 nm (sort-wave infrared, SWIR).</u> To the best of my knowledge, this light source is the first realization of such a broad spectral range for an optical vortex. To carry out the light source, I divided the project into two parts. ***(Specific Aim 1)*** <u>First is the preparation of a CEP controllable algorithm to quantitatively and arbitrarily manage the CEP of generated pulses</u>. ***(Specific Aim 2)*** <u>Second is to generate ultrabroadband vortex pulses in the SWIR range.</u>

３．研究の方法

(Specific Aim 1) **Develop an algorithm for CEP control of synthesized pulses.**

A schematic experimental setup is depicted in Fig. 1, which consists of three parts including a lab-built SWIR optical parametric amplifier (OPA), a CEP detector, and a lab-built algorithm. The SWIR OPA is used to generate an over-octave-spanning spectrum, ranging from 900 to 2400 nm [1-7], as depicted in Fig. 2. Another key feature is the application of a Mach-Zehnder-type interferometer (MZI) to control the CEP for the entire range of the over-octave-spanning spectrum with two CEP modulators, which manage the shared spectral components on the short- (900-1450 nm) and long- (1450-2400 nm) wavelength sides. The CEP modulators are simultaneously controlled by a lab-built algorithm as a function of time. The modulated pulses output from the CEP modulators are linearly superposed to form a synthesized waveform.

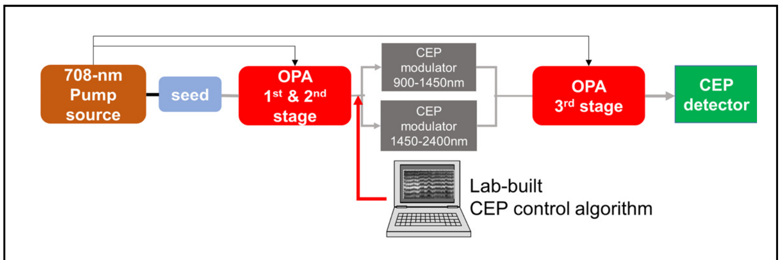

Fig. 1: Setup for arbitrary CEP control of synthesized pulses.

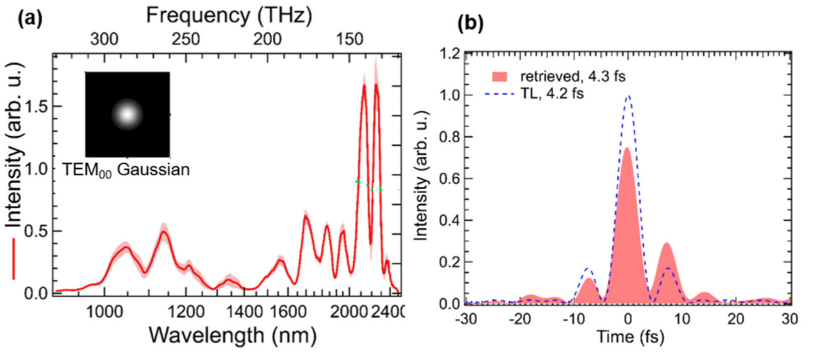

Fig. 2: (a) Ultrabroadband SWIR spectrum. (b)Transform-limit pulse (filled-curve) and retrieved pulse (dashed-line).

***(Specific Aim 2)* Develop a vortex laser in the SWIR range.**
A schematic experimental setup is depicted in Fig. 3. There are two parts, including the SWIR OPA used to generate a single-cycle TEM_{00} Gaussian beam, as depicted in the inset of Fig. 2(a), and a Sagnac interferometer utilized to convert the TEM_{00} Gaussian beam into an optical vortex.

The Sagnac interferometer is used since it is merely composed of dispersion-free mirrors and a beam splitter. There is almost no limitation for the bandwidth if a good design for the coating of the mirrors and beam splitter is performed. In this case, the generated optical vortex is expected to keep almost the same pulse duration as the input TEM_{00} Gaussian beam after the mode transformation. I have checked theoretically the operation parameter for the Sagnac interferometer. The amount of linear displacement for the mirrors is analytically confirmed to lead to a well-defined optical vortex in the whole wavelength range from 900 nm to 2400 nm. My analysis reveals the feasibility to realize such a broadband optical vortex with the Sagnac interferometer.

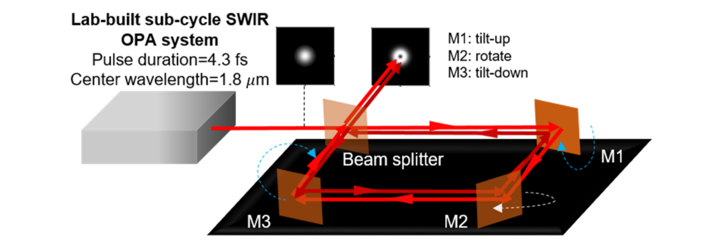

Fig. 3: Setup for mode conversion via a Sagnac interferometer.

４．研究成果

***(Specific Aim 1)* Develop an algorithm for CEP control of synthesized pulses.**
There are two procedures in this part: (A) Prepare an algorithm of user-defined functions of time for controlling the CEPs of two few-cycle pulses with adjacent spectral ranges, which are synthesized to form a single-cycle pulse, as depicted in Fig. 4(a). (B) Confirm the feasibility of the algorithm in the lab-built laser system [1] with a waveform synthesis scheme consists of two CEP modulators. The waveform synthesis technique is designed for the CEP control since it enables more flexibilities to control the CEP of each wavelength component for various synthesized waveforms. For (A) and (B), I developed the algorithm and performed the experiment, as shown in Figs. 4(b)-(e). The experimental result (Fig. 4(d)) shows a great agreement with my initial design (Fig. 4(c)) by modulating the CEP of each composite pulse ($\varphi_{\mathrm{CE}}^{(\mathrm{S})}$ and $\varphi_{\mathrm{CE}}^{(\mathrm{L})}$) with triangular waveforms displayed in Fig. 4(b). The present result is published in ref. [8].

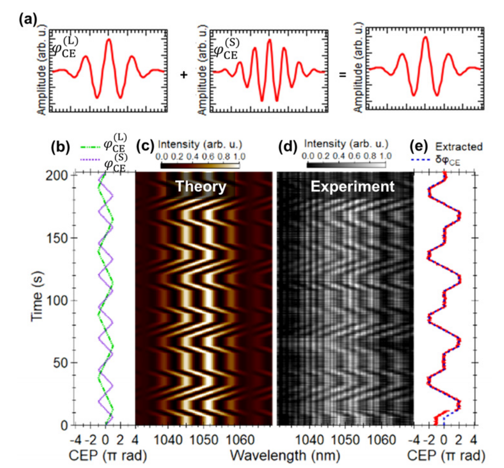

Fig. 4: Results for arbitrary CEP control of a synthesized waveform. (a) Concept for waveform synthesis. (b) Input triangular waveforms of time for the CEP shifts of each composite pulses. (c) Ideal and (d) experimental spectrograms for the synthesized pulse. (e) Extracted CEP shift from the spectrogram (dotted curve) compared with the initial design (dashed curve).

***(Specific Aim 2)* Develop a vortex laser in the SWIR range.**
There are two necessary procedures in this part: (A) Preparation of an ultrabroadband TEM_{00} Gaussian beam and (B) conversion of the generated TEM_{00} Gaussian pulses into vortex pulses. For (A), we have successfully generated a sub-optical-cycle SWIR TEM_{00} Gaussian beam with wavelength range spanning from 900 nm to 2400 nm [1-7], as shown in Fig. 2. For part (B), a Sagnac interferometer [7] is applied to transform the generated TEM_{00} Gaussian beam into an achromatic optical vortex without additional dispersion. The generated optical vortices at different wavelengths are displayed in Fig. 5. The first row shows the vortex profile measured by inserting different bandpass filters and the second row shows the interference spiral pattern by using a Mach Zehnder interferometer to superpose the generated optical vortices with a TEM_{00} Gaussian beam directly output from the SWIR OPA. The spiral patterns shown in Fig. 5 confirm that the generated optical vortices all possess a topological

charge (ℓ) of +1. This is the first realization of such a broadband optical vortex with a well-defined topological charge.

Furthermore, I applied the CEP control technique realized in ***(Specific Aim 1)*** to control the CEP shift of the generated optical vortices. To characterize the feasibility of the CEP control in the optical vortex, I superposed the fundamental wave (FW) of the optical vortex with the second-harmonic generation (SHG) of the TEM_{00} Gaussian beam mentioned above. The concept is depicted in Fig. 6(a). The extracted phase for the interference region can be written as $\varphi_{\mathrm{CE}} = (\varphi_{\mathrm{CE}}^{(\mathrm{S})} - \ell\phi) - 2\varphi_{\mathrm{CE}}^{(\mathrm{L})}$, where ϕ is the azimuthal angle for the optical vortex. Likewise, the interference patterns are shown to form spiral patterns. To see the influence of the CEP on the vortex beam, CEP phases $\varphi_{\mathrm{CE}}^{(\mathrm{S})}$ and $\varphi_{\mathrm{CE}}^{(\mathrm{L})}$ are modulated with time. I used a part of the SHG and FW of the TEM_{00} Gaussian beam for an $f-2f$ interferometry measurement to check the resulting CEP modulation simultaneously with the pattern observation. Figure 6(b) shows an example by modulating both $\varphi_{\mathrm{CE}}^{(\mathrm{S})}$ and $\varphi_{\mathrm{CE}}^{(\mathrm{L})}$ with triangular waveforms. The resulting phase modulation $\Delta\varphi_{\mathrm{CE}}$ (dotted curve in Fig. 6(b)), extracted from interference fringes (below) measured by a conventional $f-2f$ interferometer, is also a triangular waveform. The interference spiral patterns with different $\Delta\varphi_{\mathrm{CE}}$ are depicted in Fig. 6(c). Upper rows for each phase shift are theoretical results calculated based on the experimental conditions and the lower rows are their experimental counterparts. We observe a clockwise rotation as $\Delta\varphi_{\mathrm{CE}}$ decreases in Fig. 6(c), where the theoretical and experimental results are in a good agreement. The present result is expected to provide new ideas in the nonlinear singular optics and strong-field physics.

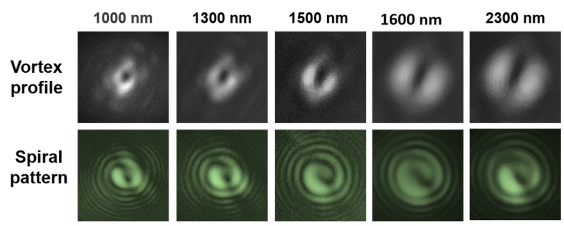

Fig. 5: Experimental beam profiles. First row: vortex beam profile. Second row: Interference patterns between a TEM_{00} Gaussian and the vortex beams shown above. The spiral patterns confirm the topological charge $\ell = +1$ for all wavelength components.

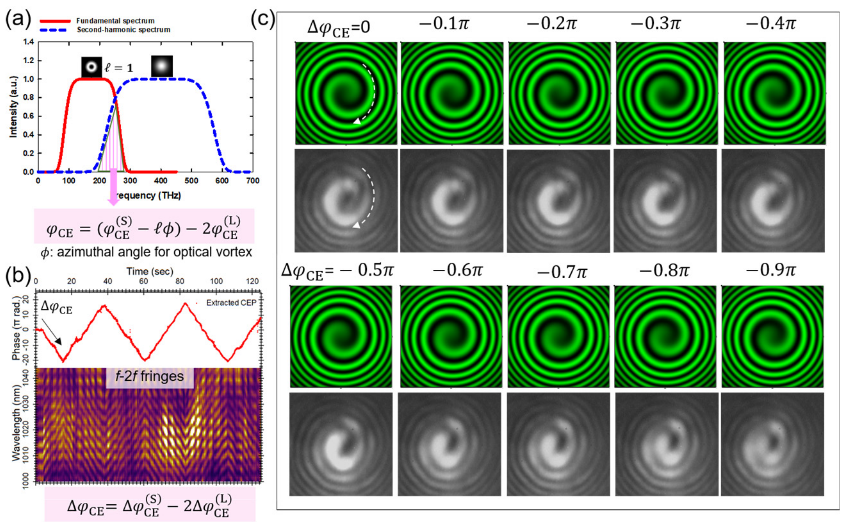

Fig. 6: (a) Interference between a fundamental vortex beam and a second-harmonic TEM_{00} Gaussian beam. (b) $f-2f$ fringes (below) and extracted CEP shift (upper) during the CEP modulation. (c) Interference spiral patterns measured with the decrease of $\Delta\varphi_{\mathrm{CE}}$.

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５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　1件／うちオープンアクセス　1件）

１．著者名 Lin Yu-Chieh、Midorikawa Katsumi、Nabekawa Yasuo	４．巻 30
２．論文標題 Carrier-envelope phase control of synthesized waveforms with two acousto-optic programmable dispersive filters	５．発行年 2022年
３．雑誌名 Optics Express	６．最初と最後の頁 10818～10818
掲載論文のDOI（デジタルオブジェクト識別子） 10.1364/OE.447820	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計9件（うち招待講演　6件／うち国際学会　2件）

１．発表者名 Yu-Chieh Lin
２．発表標題 Optical parametric amplifier of a sub-cycle shortwave infrared pulses
３．学会等名 OPT2021 symposium（招待講演）
４．発表年 2021年

１．発表者名 Yu-Chieh Lin
２．発表標題 Carrier-envelope phase control of synthesized waveforms with two acousto-optic programmable dispersive filters
３．学会等名 Q-LEAP Attosecond Research Meeting（招待講演）
４．発表年 2021年

１．発表者名 Yu-Chieh Lin
２．発表標題 Carrier-envelope phase control of synthesized waveforms with two acousto-optic programmable dispersive filters
３．学会等名 The 9th RAP Symposium in RIKEN（招待講演）
４．発表年 2022年

１．発表者名
Yu-Chieh Lin

２．発表標題
Optical parametric amplifier of a sub-cycle shortwave infrared pulses

３．学会等名
CLEO 2022（招待講演）（国際学会）

４．発表年
2022年

１．発表者名
Yu-Chieh Lin, Yasuo Nabekawa, Katsumi Midorikawa

２．発表標題
Carrier-envelope phase control of over-octave-spanning synthesized spectra using multiple acousto-optic programmable dispersive filters

３．学会等名
The 42nd Annual Meeting of the The Laser Society Japan

４．発表年
2022年

１．発表者名
Yu-Chieh Lin, Yasuo Nabekawa, Katsumi Midorikawa

２．発表標題
Stabilization of carrier-envelope phase with multiple acousto-optic programmable dispersive filters

３．学会等名
The 69th JSAP Spring Meeting 2022

４．発表年
2022年

１．発表者名
Yu-Chieh Lin, Katsumi Midorikawa, Yasuo Nabekawa

２．発表標題
Arbitrary carrier-envelope phase control of over-octave-spanning synthesized waveform using multiple AOPDFs

３．学会等名
OPTICS & PHOTONICS International Congress 2022（国際学会）

４．発表年
2022年

1．発表者名 Yu-Chieh Lin
2．発表標題 Generation of optical vortex in ultrashort laser
3．学会等名 Meeting at Molecular Chirality Research Center in Chiba University（招待講演）
4．発表年 2020年

1．発表者名 Yu-Chieh Lin
2．発表標題 Optical parametric amplifier of a sub-cycle shortwave infrared pulses
3．学会等名 Q-LEAP Attosecond Research Meeting（招待講演）
4．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関