Proposal to generate an isolated monocycle X-ray pulse by counteracting the slippage effect in free-electron lasers

A monocycle pulse is an ultrashort light wave whose pulse length is reduced to the theoretical lower limit, namely, the wavelength of light. In the visible and infrared regions, the generation of monocycle pulse with a conventional laser has become a mature technology, and ultrashort pulses with a pulse length of several femtoseconds are already available that are used to probe ultrafast dynamics such as the chemical reaction and physical phenomenon. On the other hand, the generation of monocycle pulses in the X-ray region, i.e., the generation of monocycle X-ray free electron laser (XFEL) pulses, has not been realized and possible methods of producing them are yet to be proposed.

In XFELs, a high energy electron beam injected to an undulator generating a periodic magnetic field works as the laser medium. During the amplification process of XFEL, density modulation is performed in an electron beam with a period equal to the laser wavelength, which is called "microbunch," and the pulse length of the XFEL is roughly equal to that of the microbunch. Thus, it seems possible to generate a monocycle XFEL pulse if the microbunch is shortened to the scale of the laser wavelength (single microbunch) as shown in Fig. 1(a). In practice, however, the pulse length increases while the electron beam travels along a sinusoidal orbit in the undulator because the light wave overtakes the electron beam and shifts forward. As a result, the pulse length of XFEL generated by a single microbunch increases proportionally to the number of undulator periods.

The above phenomenon is generally called an optical slippage effect and has been the biggest obstacle to the realization of monocycle XFEL pulses. We have proposed a new scheme to suppress this effect using the interference of light waves to control the pulse length of XFEL, and we have numerically demonstrated its principle and feasibility [1].

In the proposed scheme, an electron beam with a microbunch having an irregular interval is injected to an undulator whose magnetic field amplitude is varied along its axis. What is important is that the n-th microbunch interval (=λ_n) is equal to the slippage length of the n-th undulator period. The simplest example that satisfies this requirement is shown in Fig. 1(b), where λ_n linearly changes with the period number n, and such a microbunch is referred to as a "chirped microbunch."

Now let us consider the radiation process of an electron beam with a chirped microbunch using Fig. 2. Figure 2(i) shows the outline of the current profile of the electron beam with a chirped microbunch, in which the electron beam current *I* is given as a function of the longitudinal position *s*. In this example, 11 microbunches are contained with the interval (λ_1–λ_{10}) that linearly decreases. The electron beam is then injected to an undulator with the n-th slippage length equal to λ_n. In order to satisfy this condition, a special undulator with the magnetic field amplitude decreasing linearly, which is called a tapered undulator, can be used. Figure 2(ii) shows schematically the waveform of light generated by the chirped microbunch after the

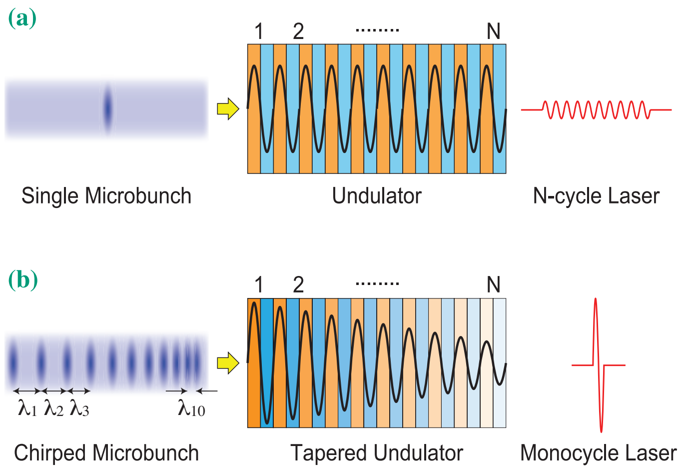

Fig. 1. Radiation process of an electron beam with **(a)** a single microbunch and **(b)** a chirped microbunch.

electron beam passes through the 1st period, where the electric field of radiation E is given as a function of s. Thus, the electron beam wiggling once emits light with the waveform similar to its current profile. It should be emphasized here that the light wave is shifted forward by the distance λ_1 because of the optical slippage effect. The peak indicated by an arrow denotes the position of the light pulse (hereinafter, resonant pulse) generated by the microbunch located at the tail position, which is shown by the dashed line and is defined as the origin of the coordinate. At this stage, the position of the resonant pulse is λ_1 ahead of the origin.

Figure 2(iii) shows the waveform of light after the 2nd period. The red solid line indicates the waveform generated at the 1st period, while the blue dotted line indicates that at the 2nd period. The slippage length at the 2nd period is λ_2 not λ_1, and thus the resonant pulse is located at $s = \lambda_1 + \lambda_2$. In Figs. 2(iv) and 2(v), the waveforms of light after the 3rd and 4th periods are shown in green dashed and cyan chain lines, respectively. The red solid lines shown in Fig. 2(vi) denote the waveforms created between the 1st and 10th periods, while the dashed line denotes the waveform created by summing all of them. It is easy

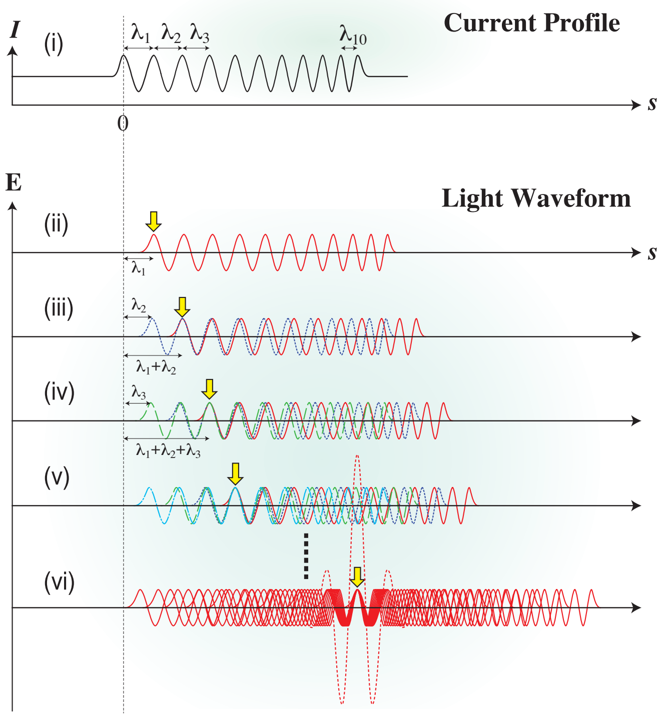

Fig. 2. Schematic illustration to explain the principle of operation of the proposed scheme. **(i)** Current profile of the electron beam with a chirped microbunch. **(ii)–(v)** Light waveforms emitted by the electron beam after the 1st–4th undulator periods. **(vi)** Light waveforms after the 10th period.

to understand that the intensity of the resonant pulse is significantly enhanced by constructive interference, while those of other pulses are suppressed by destructive interference. The intensity contrast between the resonant and other pulses can be controlled by the change rate of the slippage length ($\lambda_1 - \lambda_{10}$), and a monocycle pulse can be ultimately generated.

One idea for the practical implementation of the above principle in XFELs is in the so-called high gain harmonic generation (HGHG) FELs, in which a seed laser is upconverted through interaction with an electron beam moving in an undulator. This is referred to as monocycle harmonic generation (MCHG), and the most important advantage of MCHG over the normal HGHG is that the monocycle pulse can be upconverted without the pulse lengthening due to the optical slippage.

In order to demonstrate the feasibility and performance of MCHG, we carried out FEL simulations with the assumption that a monocycle pulse with a central wavelength of 60 nm and a pulse energy of 10 μJ is used as a seed laser to drive the MCHG scheme with an electron beam having an energy of 2 GeV and current of 2 kA. It has been found that a monocycle pulse with a peak power of 1.2 GW and pulse length of 46 as (attoseconds) is generated at the 7th harmonic, i.e., at the central wavelength of 8.6 nm.

The above example validates the feasibility of the proposed scheme in the soft X-ray region; however, it should be emphasized that no theoretical limit exists for the available wavelength. It is thus expected to open up a new field of research, so to speak, "zeptosecond science," by applying this scheme in the hard X-ray region, which will enable us to generate a monocycle X-ray pulse with a pulse length of several hundreds of zeptoseconds.

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Reference

[1] *T. Tanaka: Phys. Rev. Lett.* ***114*** *(2015) 044801.*