EXPERIMENTAL STUDY OF A TWO-COLOR STORAGE RING FEL *

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Abstract

Multi-color Free-electron Lasers (FELs) have been developed on linac based FELs over the past two decades. On the storage ring, the optical klystron (OK) FEL in its early days was demonstrated to produce lasing at two adjacent wavelengths with their spectral separation limited by the bandwidth of single wiggler radiation. Here, we report a systematic experimental study on the two-color operation at the Duke FEL facility, the first experimental demonstration of a tunable two-color harmonic FEL operation of a storage ring based FEL. We demonstrate a simultaneous generation of two FEL wavelengths, one in infrared (IR) and the other in ultraviolet (UV) with a harmonic relationship. The experimental results show a good performance of the two-color FEL operation in terms of two-color wavelength tunability, power tunability and power stability.

INTRODUCTION

Since the theoretical prediction and the first experimental demonstration by John Madey in 1970s [1, 2], free-electron lasers (FELs) have seen great development over the past few decades and have become increasingly attractive light sources to several scientific research fronts. A common FEL configuration requires an optical cavity to oscillate and amplify electron beam radiation and is thus called an oscillator FEL [3]. An oscillator FEL can be driven either by an electron storage ring or a linac. Oscillator FELs mainly operate in the spectral region from IR to UV. Since early 1990s, multi-color, especially two-color FEL operations have been frequently discussed and realized on several linac based FELs. The first two-color FEL operation was realized on CLIO [4], an oscillator FEL operating in the mid-infrared regime, where two FEL wavelengths were produced by the same electron beam and two undulators with different undulator strengths inside a single optical cavity. Two more linac based oscillator FELs reported their successful two-color operations later on [5, 6]. Another FEL configuration, the so-called single-pass FEL, is mainly driven by linacs and do not use an optical cavity. In these FELs, FEL beam amplification is realized via the interaction between the electron beam and the radiation it emits [7, 8] or an external laser [9, 10] in a single pass. Single-pass FELs are the dominant coherent light sources in the vacuum UV (VUV) and x-ray regimes. Recently two-color operations have also been experimentally demonstrated on several single-pass FELs [11–15] in the short-wavelength spectral regions.

Unlike in a linac, an electron beam in a storage ring is recycled and participates in the FEL interaction repeatedly over many passes. Therefore, the physics challenges for the two-color operation of a storage-ring FEL include the control and management of two competing lasing processes and maintanance of simultaneous lasing at two wavelengths in multiple passes. In this article, we report a systematic experimental study on the two-color operation at the Duke FEL facility, the first experimental demonstration on the multi-color operation of a storage ring based FEL in both IR and UV, in which, a simultaneous generation of two FEL wavelengths (IR and UV) with a harmonic relationship has been realized. The experimental results illustrate a good performance of our two-color FEL operation in terms of two-color wavelength tunability, power tunability and power stability. In addition, the two-color FEL can serve as a photon source for the two-energy gamma-ray production via Compton backscattering at the High-Intensity γ-ray Source (HIGS) [16].

EXPERIMENTAL SETUP

The operation of the Duke FEL system can use a variety of wiggler configurations with four available electromagnetic wiggler magnets, two planar OK-4 wigglers and two helical OK-5 wigglers (see Fig. 1), which provides the possibility of operating two-color FEL using the same electron beam at a single beam energy. In the harmonic two-color FEL research, three wigglers as shown in Fig. 1 are powered up, including the upstream helical OK-5 wiggler (OK-5A) and two planar OK-4 wigglers (OK-4A and OK-4B) in the middle section. The downstream OK-5 wiggler (OK-5D) was disconnected. Upstream OK-5A wiggler is used to lase at the fundamental wavelength in IR, and two downstream OK-4 wigglers in the optical klystron configuration is tuned to lase at the second harmonic in UV. The lasing wavelengths are varied by changing the strength of the magnetic field in the OK-5 and OK-4 wigglers, respectively. Two bunchers, $B1$ between OK-5A and OK-4 wigglers and $B2$ sandwiched by two OK-4 wigglers, are used to provide fine tuning of the harmonic FEL lasing. The harmonic two-color FEL lasing is realized at the fundamental wavelength

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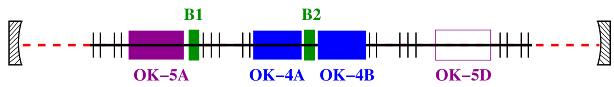

Figure 1: Wiggler configuration for the two-color FEL operation. OK-5A (helical) is used to produce the fundamental wavelength lasing in IR and two OK-4 wigglers (planar) are used to lase at the second harmonic wavelength in UV. OK-5D is disconnected.

around 720 nm (λ_1) and the second harmonic wavelength around 360 nm (λ_2). To enable lasing at two wavelengths with a harmonic relationship, a pair of FEL mirrors have been developed with two highly reflective wavelength bands centered around 720 nm and 360 nm, respectively.

Since the same electron beam is used as the shared gain medium, it is critical to keep the net lasing gains at two wavelengths close to each other. The OK-5 FEL has a relatively low gain as the helical undulator is located on the upstream side of the optical cavity with a relatively poor transverse overlap between the electron and FEL beams. The lower gain of OK-5A is compensated by operating the OK-5 FEL around 720 nm where the optical cavity has a lower loss. The optical klystron OK-4 is capable of a much higher gain and thus it is chosen to be operated at the 2nd harmonic wavelength where the cavity loss is also higher. To provide a good gain matching, the gain of the OK-4 FEL needs to be further reduced. In experiments, several tuning knobs, e.g. RF frequency detune df_{RF}, buncher $B1$ and buncher $B2$, are found to be useful for adjusting the relative gains at two wavelengths. For example, we devised a special setup of the OK-4 optical klystron to significantly reduce its gain by forcing it to lase with a low gain by tuning buncher $B2$.

All of the FEL measurements reported in this article were conducted with a single-bunch, 500 MeV e- beam in the Duke storage ring. The storage ring was set up with a set of typical working point parameters, including transverse tunes $\nu_x = 9.13$ and $\nu_y = 4.17$, and chromaticity values $\xi_x = 1.1$ and $\xi_y = 1.2$.

EXPERIMENTAL RESULTS

Wavelength Tuning

For many important research applications using a two-color laser, it is critical to have the ability to tune one of the lasing wavelengths while fixing the other. Experiments were successfully carried out to demonstrate wavelength tunability in such a manner. Figure 2 shows a case in which the fundamental wavelength λ_1 was fixed at 720 nm, while the second harmonic wavelength λ_2 was tuned from 349.98 nm to 374.09 nm with a step size of roughly 4 nm by increasing the magnetic field strength of OK-4 wigglers, which demonstrates a wavelength tuning range of 24 nm. Figure 3 shows two pairs of measured spectra, one in a strict harmonic relationship and the other with the second harmonic wavelength tuned away by 8 nm. Moreover, tuning λ_1 while fixing λ_2 at 360 nm was also achieved with a tuning range

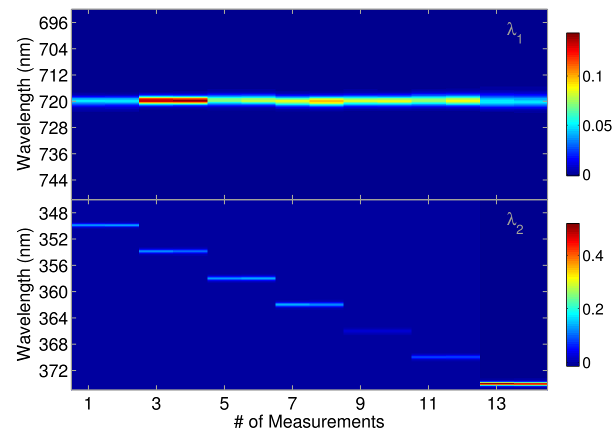

Figure 2: Single wavelength tuning in which the second harmonic λ_2 is tuned while the fundamental λ_1 is fixed. e-beam current is maintained between 15.9 mA and 16.4 mA.

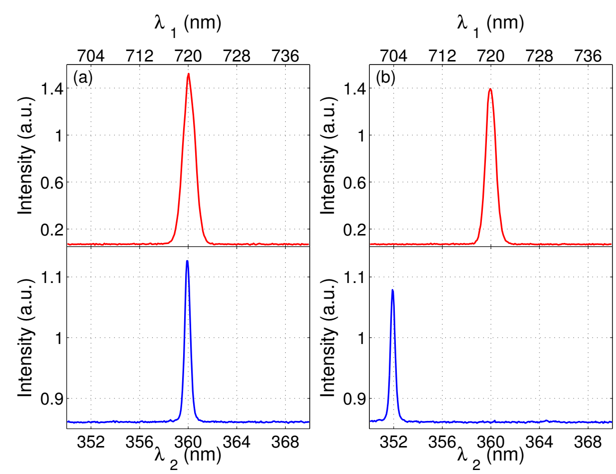

Figure 3: Measured spectra in the wavelength tuning experiment shown in Fig. 2: (a) Two wavelengths are in a strict harmonic relationship. The RMS spectral widths of λ_1 and λ_2 are $\sigma_1 = 1.00$ nm and $\sigma_2 = 0.23$ nm, respectively; (b) The second harmonic λ_2 is tuned away by 8 nm. $\sigma_1 = 0.81$ nm and $\sigma_2 = 0.19$ nm.

of roughly 60 nm (674.92 nm ~ 734.88 nm). To achieve good lasing for both FELs, the lasing gains were balanced by fine adjustments of the settings of bunchers $B1$ and $B2$.

In addition, to demonstrate wavelength tuning of the harmonic two-color lasing, the magnetic field strengths of OK-4 and OK-5 wigglers were varied simultaneously to keep two wavelengths in a strict harmonic relationship. In this case, λ_1 was tuned from 704 nm to 740 nm while λ_2 was accordingly varied from 352 nm to 370 nm. The harmonic lasing tuning range (36 nm for λ_1 or 18 nm for λ_2) was limited by the amount of overlapping of the low-loss regions of the high-reflectivity wavelength bands in IR and UV of the specially developed dual-band FEL mirrors.

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Power Control

Two FELs at two different wavelengths share the same gain medium, the electron beam. The experimental results in the previous section showing two-color lasing with wavelength tunability has clearly demonstrated our ability to provide an excellent control of the gain balance for two lasing processes, as well as a mastery of the FEL power control. Additional measurements were made to demonstrate a precise control of the partition of the FEL power for two different wavelengths using a single knob, the B1 buncher setting N_{B1}. N_{B1} represents the relative optical phase slippage between the IR laser beam and UV laser beam. It was used to switch on/off the lasing of either color. Several measurements were conducted at different levels of the single bunch current, with a natural lifetime decay of the beam current or with top-off injection to maintain the beam current. The FEL powers at two wavelengths were measured using two photodiodes after filtering out the other. The power measurements at two wavelengths were cross-calibrated using the bunch length measurements. The cross calibration of the extracted power at two wavelengths allowed us to study the levels of power modulation.

Overall, we realized a complete control of the FEL power for each of the lasing wavelength, producing stable two-color lasing with equal power, or a pre-determined power ratio in two wavelengths. During this process, the total FEL power remained roughly constant.

SUMMARY

In this article, we report a successful operation of a storage ring based harmonic two-color FEL. We have demonstrated wavelength tunability in a wide tuning range by changing one of the two lasing wavelengths or simultaneously changing both wavelengths while maintaining the harmonic relationship. Furthermore, we have demonstrated full control of the FEL power in two lasing wavelengths while maintaining the total FEL power at a fixed level. Duke storage ring is primarily operated as a photon driver for HIGS. The preliminary work on two-energy γ-beam production using the two-color FEL is well under way. This two-energy $\gamma-$ray beam will provide new possibilities for experimental nuclear physics research.

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