A TWO-COLOR STORAGE RING FEL*

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Abstract

Using different undulator configurations on the Duke storage ring, we have successfully achieved lasing with a novel two-color storage ring FEL. Using a pair of dual-band FEL mirrors, simultaneous lasing was realized in IR (around 720 nm) and in UV (around 360 nm). With this two-color FEL, we have demonstrated independent wavelength tuning of either IR or UV lasing. With careful tuning, we have also realized harmonic lasing with the UV lasing tuned to the second harmonic of the IR lasing. The tuning of harmonic two-color lasing has also been demonstrated with the locked wavelengths. Furthermore, we have demonstrated good control of the FEL power sharing between the two colors. The two-color FEL has created new opportunities to drive a two-color Compton γ-ray beam at the High Intensity γ-ray Source at Duke.

INTRODUCTION

Multi-color lasers have found many important applications in scientific research. One example is wavelength-division multiplexing, which utilizes multiple optical signals at different wavelengths multiplexed into a shared fiber for enhancing the efficiency of communication systems. Multi-color lasers with good colinearity are particularly important in research, since the laser beams of different colors can be co-propogated over a long distance, collimated and focused simultaneously. For example, two optical pulses with different wavelengths but controllable time delay can be used in pump-probe spectroscopy to measure the fast dynamics of the system under investigation. Some other applications of multi-color lasers include photomixing processes for terahertz radiation generation and differential absorption lidar. The typical approach to realize simultaneous multi-color lasing is using a dispersive or diffractive wavelength filter such as a prism or grating, either intracavity or in an external feedback cavity. Such a technology has been implemented in conventional lasers with different gain media such as dye [1,2], solid-state [3,4], semiconductor [5,6] and fiber [7]. However, the wavelength tunability of these lasers is typically limited by the bandwidth of the gain medium.

Since the theoretical prediction and the first experimental demonstration by Madey in the 1970s [8,9], free-electron lasers (FELs) have seen great development over the past few decades, and have become increasingly attractive light sources in a number of research areas. A common low-gain FEL configuration uses an optical cavity to trap and amplify electron beam radiation in a device termed an oscillator FEL [10]. 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 vacuum UV. The natural advantages of an FEL such as its broadband gain medium (an electron beam) and the single optical cavity configuration make the oscillator FEL an excellent device for the multi-color lasing with good wavelength tunability and colinearity. Since early 1990s, multi-color, especially two-color FEL operations have been developed and realized with several linac based FELs. The first two-color linac FEL operation was demonstrated on CLIO [11], 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 other linac based oscillator FELs reported successful two-color operations later [12,13]. Another FEL configuration, the high-gain single-pass FEL, is mainly driven by linacs and does not use an optical cavity. In these FELs, the amplification of the FEL beam is realized in a single pass via the interaction between the electron beam and its radiation in a long undulator array [14,15] or with an external laser [16,17]. Single-pass FELs are now high-performance coherent light sources in the extreme UV and x-ray regimes. Recently two-color operations have also been experimentally demonstrated with several single-pass FELs [18–22] in the short-wavelength spectral regions.

Unlike in a linac, an electron beam in a storage ring is recycled so that it participates in the FEL interaction repeatedly over a large number of 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. The first experimental demonstration of two-color FEL operation at the Duke FEL facility, in which simultaneous generation of two FEL wavelengths (IR and UV) with a harmonic relationship was realized, was reported in Ref [23]. In this article, we report an experimental study of two-color lasing using a different undulator configuration. The experimental results show good performance of this two-color operation in terms of wavelength tunability, power tunability and power stability. In addition, this two-color FEL can serve as a photon

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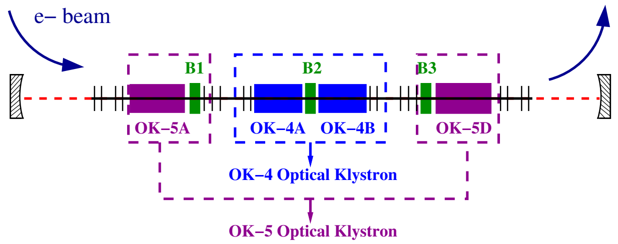

Figure 1: A four-undulator configuration for two-color FEL operation. All the four undulators are powered up, with two OK-4 undulators and two OK-5 undulators forming two sets of interleaved optical klystrons.

source for the two-energy γ-ray production via Compton backscattering at the High Intensity γ-ray Source [24].

EXPERIMENTAL SETUP

The operation of the Duke FEL system can use a variety of undulator configurations with four available electromagnetic undulator magnets, two planar OK-4 undulators and two helical OK-5 undulators (see Figure 1). This provides the possibility of operating a multi-color FEL using the same electron beam and a shared optical cavity. We have achieved two-color lasing with both three-undulator and four-undulator configurations. In the three-undualtor configuration, three undulators are powered up, including the upstream OK-5 undulator (OK-5A) and two OK-4 undulators (OK-4A and OK-4B) as an optical klystron in the middle section. The downstream OK-5 undulator (OK-5D) is disconnected. In the four-undulator configuration, OK-5D undulator is also energized so that two OK-5 undulators also form an optical klystron as shown in Figure 1. In this two-color FEL, OK-5 undulators are tuned to lase at λ_1 in IR while OK-4 undulators to lase at λ_2 in UV.

By changing either the electron beam energy or undulator field strength, the FEL lasing wavelength can be tuned around the center wavelength of the undulator radiation, λ_{cen},

$$\lambda_{\mathrm{cen}} = \frac{\lambda_u}{2\gamma^2}(1 + p\frac{K^2}{2}), \tag{1}$$

where λ_u is the undulator period, $\gamma = E/(mc^2)$ is the Lorentz parameter for an electron with energy E and rest mass m, $K = eB_0\lambda_u/(2\pi mc^2)$ is the undulator strength of an undulator with peak magnetic field strength B_0, and the polarization parameter $p = 1$ (or 2) for a planar (or helical) undulator. The wavelength tuning is done by changing the magnetic field strength in the OK-4 and OK-5 undulators. Further, three buncher magnets, $B1$, $B2$ and $B3$ (see Figure 1) are used to provide fine tuning of the two-color FEL lasing, both the wavelength and power level.

The two-color FEL lasing is typically tuned to the IR wavelength around 720 nm (λ_1) and the UV wavelength around 360 nm (λ_2), and allows for harmonic lasing with $\lambda_1 \simeq 2\lambda_2$. To enable lasing at two wavelengths with such a large spectral separation, a pair of dual-band FEL mirrors

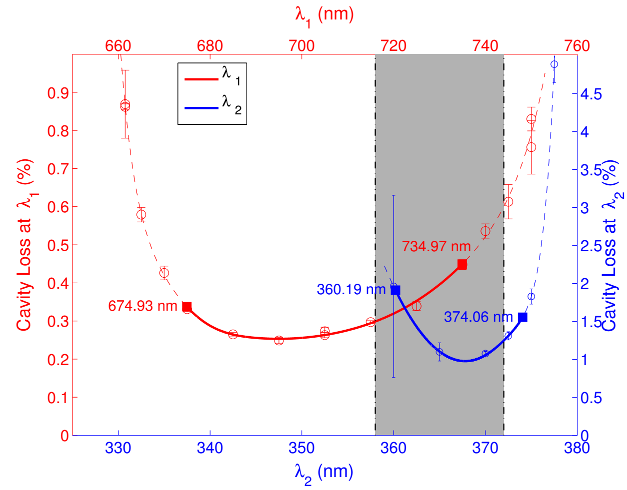

Figure 2: Measured round-trip FEL cavity losses in two high-reflectivity bands as a function of the wavelength. The mirrors have degraded after being exposed to the electron beam radiation for a substantial amount of time compared to the case with fresh mirrors reported in Ref [23]. The solid parts of the curves represent the wavelength tuning range of one color while fixing the lasing wavelength of the other color. The shaded region enclosed by the black dash-dot lines represents the tuning range for harmonic wavelength tuning ($\lambda_1 \simeq 716 \sim 744$ nm; $\lambda_2 \simeq 358 \sim 372$ nm).

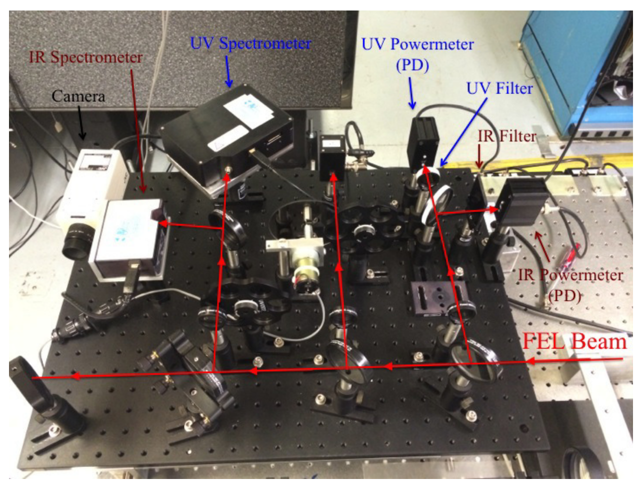

Figure 3: Optical system for two-color FEL diagnostics. The power measurement for each color is done using a photodiode after filtering out the signal of the other color. The wavelength measurements are done by two spectrometers covering IR and UV wavelength ranges, respectively.

have been developed with two highly reflective wavelength bands centered around 720 nm and 360 nm, respectively. Figure 2 shows the measured round-trip losses in the IR and UV bands after the FEL mirrors have degraded by substantial exposure to the electron beam radiation. As shown in Figure 2, the minimum cavity loss in UV is roughly four times as high as that in IR.

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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 since the helical undulators are located about 10 m away from the center of the optical cavity. The lower gain of OK-5 undulators is compensated by operating the OK-5 FEL in IR where the optical cavity has a lower loss (see Figure 2). Located in the middle of the optical cavity, the OK-4 FEL has a higher gain and is chosen to be operated in UV where the cavity loss is also higher. To provide good gain matching, the gain of the OK-4 FEL needs to be further reduced. In these experiments, several tuning knobs, e.g. RF frequency detune $d f_{\mathrm{RF}}$ which controls FEL detune, bunchers $B1$, $B2$ and $B3$, are found to be useful for adjusting the relative gains at the 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 lower gain via the tuning of buncher $B2$.

The FEL measurements reported in this article were conducted with the four-undulator configuration, the cavity loss shown in Figure 2 and a single-bunch, 500 MeV electron beam in the Duke storage ring. Figure 3 is a picture of a typical FEL optical diagnostic system to characterize the two-color FEL beams. The FEL spectra at two wavelengths are measured using two spectrometers from Ocean Optics, a USB4000 spectrometer with a wavelength range of 477 – 1146 nm, and a HR4000 spectrometer with a wavelength range of 220 – 447 nm. The extracted FEL power in each color is measured using a photodiode after filtering out the signal of the other color. The intracavity power in each color can be estimated by properly calibrating the two photodiodes with the FEL active power.

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. In Ref [23], we have demonstrated the tuning of λ_1 (IR) with a large tuning range while fixing λ_2 (UV) using the three-undulator configuration. Figure 4 shows a tuning using the four-undulator configuration in which λ_1 was fixed at 720.06±0.07 nm, while λ_2 was tuned from 374.06 nm to 360.19 nm, demonstrating a wavelength tuning range of $\Delta\lambda_2 \approx 14$ nm. Such wavelength tuning was achieved by varying the magnetic field strength of OK-4 undulators as the primary tuning knob as well as the setting of buncher B2 as an auxiliary knob for fine wavelength adjustments. Since B2 was a shared buncher by OK-4 and OK-5 optical klystrons, the OK-5 undulators, as well as B1 and B3 were also tuned to compensate for the small wavelength shift of λ_1, so that λ_1 stayed fixed at 720 nm. Figure 5 shows two of measured spectra normalized to their respective peak intensity, one in the second harmonic relationship and the other with λ_2 tuned away from $\lambda_1/2$ by 8 nm. It should be noticed that the signal-to-noise ratio of UV spectra in Figure 5(a) is much lower than other measured

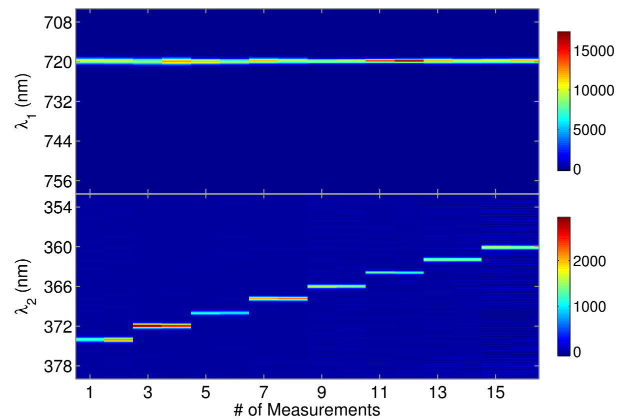

Figure 4: Single wavelength tuning. λ_2 is tuned while the fundamental λ_1 is fixed. The beam current is maintained between 12.2 mA and 12.7 mA.

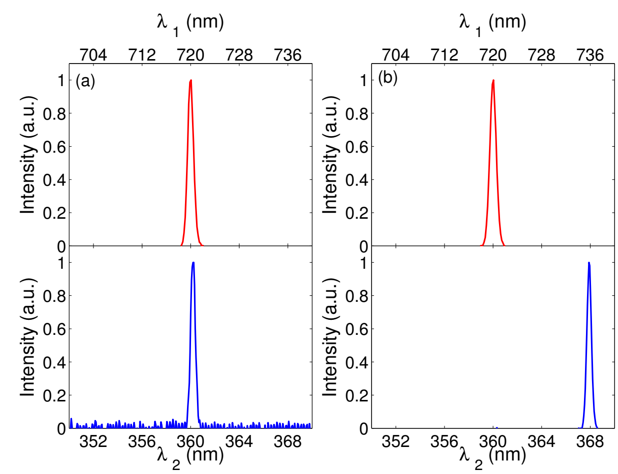

Figure 5: Measured spectra (normalized) in the wavelength tuning measurement shown in Figure 4: (a) $\lambda_1 = 719.99$ nm; $\lambda_2 = 360.19$ nm. The rms spectral widths of λ_1 and λ_2 are $\sigma_1 = 0.49$ nm and $\sigma_2 = 0.20$ nm, respectively; (b) $\lambda_1 = 720.00$ nm; $\lambda_2 = 367.91$ nm. $\sigma_1 = 0.53$ nm and $\sigma_2 = 0.19$ nm.

spectra, indicating that this spectral region is close to the lower wavelength limit for the UV lasing due to large cavity loss (See Figure 2).

To demonstrate the wavelength tuning of harmonic two-color lasing, the magnetic field strengths of OK-4 and OK-5 undulators as well as bunchers were varied simultaneously to keep two wavelengths in the second harmonic relationship. In this case, λ_1 was tuned from 716.15 nm to 744.08 nm ($\Delta\lambda_1 \simeq 28$ nm) while λ_2 was accordingly varied from 358.25 nm to 371.99 nm ($\Delta\lambda_2 \simeq 14$ nm). The wavelength tuning range of harmonic lasing was limited by the amount of overlap 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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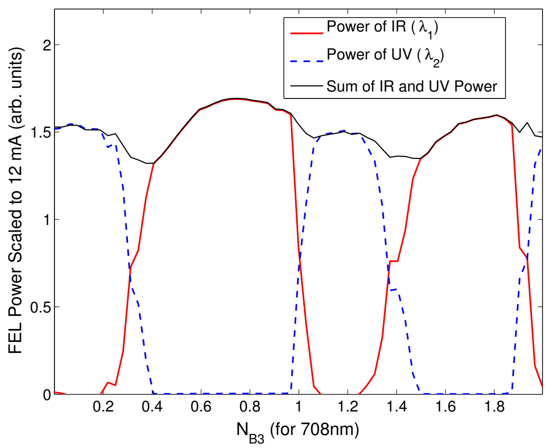

Figure 6: Two-color FEL power control using N_{B3}. A roughly 100% power modulation for IR (solid red) and UV (dashed blue) was achieved with the total power (solid black) maintained stable with a 6.8% power variation. The beam current was maintained between 12.2 and 12.5 mA with top-off injection. $N_{B1} = 0$; $N_{B2} = 0.68$ for 367 nm. The average λ_1 and λ_2 is 709.17 nm and 367.01 nm, respectively.

Power Control

The two lasing processes 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 have clearly demonstrated the capability of providing effective 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 partitioning of the FEL power for two different wavelengths by adjusting N_B, the relative optical phase slippage between the laser and electron beams produced by a buncher. Power control via N_{B1} tuning has been demonstrated for the three-undulator configuration in Ref [23]. Since OK-5 is an optical klystron in the four-undulator configuration, it is found that buncher B1 or B3 can be used as a knob to control the FEL power partition in two colors without significantly impacting the lasing wavelength of OK-4 (λ_2). For example, the two-color power tuning using B3 is shown in Figure 6, where the measured extracted FEL powers are first linearly scaled to 12 mA and then cross-calibrated with P_{FEL}, the direct FEL power emitted by the electron beam in the FEL interaction. P_{FEL} can be written as [25–27]

$$P_{\text{FEL}} \approx \alpha \, P_{\text{syn}} \, \frac{\sigma_{\text{FEL}}^2 - \sigma_0^2}{\sigma_{\text{FEL}}}, \qquad (2)$$

where P_{syn} is the total synchrotron radiation power emitted by the electron bunch in the entire storage ring; α is a numerical factor depending on the undulator configuration and FEL operation conditions; σ_{FEL} and σ_0 are the relative electron beam energy spread with FEL turned on and off, respectively. The electron beam energy spread is determined from the electron bunch length which is measured using an image dissector tube. Further, in steady state operation P_{FEL} balances against the total cavity loss and thus is proportional to the total intracavity power. Therefore, the cross calibration of the extracted power at two wavelengths allows us to study the levels of intracavity power modulation. As shown in Figure 6, a roughly 100% power modulation for IR and UV was achieved while the total FEL power is maintained quite stable within 6.8% (rms). The periodic power modulation in this measurement can be attributed to the gain modulation mechanism of an optical klystron, where, by tuning N_{B3}, the IR beams emitted in OK-5A and OK-5D produce constructive and destructive inteference alternately for electrons of a certain energy. As shown in the previous sections, the bunchers are used not only to balance the gain for two colors but as an auxiliary knob for fine wavelength adjustments. Therefore, accompanying the power modulation, the wavelength of IR lasing is periodically shifted around the mean value (709.17 nm) by about 6.43 nm (0.9%), while the wavelength of UV lasing is maintained constant at 367.01 ± 0.02 nm.

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

Two-color FEL Operation with Three-undulator Configuration

Our two-color FEL was first successfully operated using a three-undulator configuration with OK-5A and two OK-4 undulators (see Figure 1). Using this configuration, we demonstrated precision wavelength control and tuning, as well as full control of FEL power in two colors. Details on the storage ring setup and experimental results can be found in Ref [23]. With the same set of FEL mirrors which were fresher with less radiation induced degradation, the wavelength range of UV single wavelength tuning was larger with $\Delta\lambda_2 \simeq 24$ nm. The wavelength tuning ranges with harmonic lasing were also larger with $\Delta\lambda_1 \simeq 36$ nm and $\Delta\lambda_2 \simeq 18$ nm. In addition, the FEL power partition between the two colors could be well controlled by tuning the buncher B1. The two-color power stability was also examined with the three-undulator configuration and found to be related to many factors such as the stability of FEL optical axes due to the movement of FEL mirrors and the variation of the FEL cavity detune due to the temperature change. We also studied the temporal structure of the two-color beams under various operation conditions.

SUMMARY

In this paper, we report the successful operation of a two-color FEL using a four-undulator configuration. We have demonstrated wavelength tunability in a wide range by changing one of the two lasing wavelengths or simultaneously changing both wavelengths while maintaining the second harmonic relationship in wavelength. Furthermore,

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we have demonstrated full control of the FEL power in two colors while maintaining the total FEL power at a steady level. The Duke storage ring is primarily operated as a photon driver for the High Intensity γ-ray Source. The preliminary work on two-color γ-beam production using the two-color FEL is well under way. This two-color $\gamma-$ray beam will provide new possibilities for experimental nuclear physics research.

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