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A Widely Tunable Two-Color Free-Electron Laser on a Storage Ring

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With a wide wavelength tuning range, free-electron lasers (FELs) are well-suited for producing simultaneous lasing at multiple wavelengths. We present the first experimental results of a novel two-color storage ring FEL. With three undulators and a pair of dual-band mirrors, the two-color FEL can lase simultaneously in infrared (IR) around 720 nm and in ultraviolet (UV) around 360 nm. We have demonstrated independent wavelength tuning in a wide range (60 nm in IR and 24 nm in UV). We have also realized two-color harmonic operation with the UV lasing tuned to the second harmonic of the IR lasing. Furthermore, we have demonstrated good power stability with two-color lasing, and good control of the power sharing between the two colors.

In many research applications, it is highly desirable to operate a single laser system with several wavelengths simultaneously, especially if the laser beams of different colors can be produced with nearly perfect colinearity and collimation to achieve good spatial overlap when focused. Other desirable properties include independent adjustment of lasing wavelengths and full control of the lasing power for each color. A multi-color laser has a wide range of applications in a variety of research areas, including two-color pump-probe experiments [1–3], two-photon spectroscopy [4–6], excited-state spectroscopy [7, 8], coherent anti-Stokes Raman spectroscopy [9, 10], and for the generation of tunable laser beams using nonlinear crystals in the terahertz (THz) [11, 12], infrared (IR) [13, 14], and ultraviolet (UV) or extreme UV regions [15, 16]. Since the 1970s, two-color laser operation has been realized using several types of conventional lasers including dye lasers [17–20], Ti:sapphire lasers [21–24], diode lasers [25, 26], and fiber lasers [27–29] by exploring their respective wavelength tunability typically in the visible or IR spectral region.

Unlike conventional lasers with lasing wavelengths limited by the energy states of the gain medium, a free-electron laser (FEL) [30], employing the electron beam as a broadband gain medium, can operate in a wide wavelength range by changing either the electron beam energy or magnetic field strength of the FEL undulator. The wavelength tunability makes the FEL a unique class of lasers well-suited for multi-color lasing operation. Multi-color FEL operation was first observed with an optical klystron [31] storage ring FEL with two adjacent simultaneous lasing wavelengths in the visible spectrum (typically separated by a few nm) [32]. Two-color FEL operation was further explored using a linear accelerator based FEL in the infrared region using a single electron beam, a common broadband IR resonator, and two independent undulators with different magnetic field settings [33–35]. More recently, with single-pass linac FELs, two-color lasing has been demonstrated in the x-ray region using undulators with slightly different settings [36–38], and in the extreme UV region using two seeding laser pulses of slightly different wavelengths [3].

In this Letter, we report the first experimental demonstration of widely tunable two-color lasing with a storage ring FEL oscillator. Unlike the situation in a linear accelerator, the electron beam circulating in the storage ring participates in the FEL interaction during each pass through the FEL undulators. Therefore, the lasing processes at two different wavelengths not only share the same gain medium (electron beam), but also have to build up their respective optical intensities in multiple passes to reach saturation. For this two-color FEL, the main challenges include how to match the gains of two lasing processes, how to tune lasing wavelengths, and how to control the lasing power of each color in steady state operation.

The Duke FEL system [39] can be configured in multiple ways to produce lasing inside the 53.7 meter long, near-concentric, two-mirror FEL optical cavity which has a 358 ns round-trip time. It uses one or more of the four available electromagnetic undulators: two planar OK-4 undulators (33 periods each) in the middle of the straight section and two helical OK-5 undulators (30 periods each) outboard (Fig. 1). 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},

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

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, $K = eB_0\lambda_u/(2\pi mc^2)$ describes the undulator strength, and the polarization parameter $p = 1$ (or 2) for a planar (or helical) undulator, respectively. In this two-color FEL, three undulators are energized using two independent power supplies to allow lasing at two wavelengths—the upstream helical OK-5A undulator at λ_1 and an optical klystron consisting of planar OK-4B and OK-4C undulators at λ_2, while the downstream OK-5D undulator is switched off. The two lasing wavelengths can be tuned by changing the strength of the OK-5 and OK-4 undulators, respectively. Two bunchers, $B1$ between OK-5A and OK-4B undulators and $B2$ between two OK-4 undulators, are used to provide control and fine-tuning of two-color lasing.

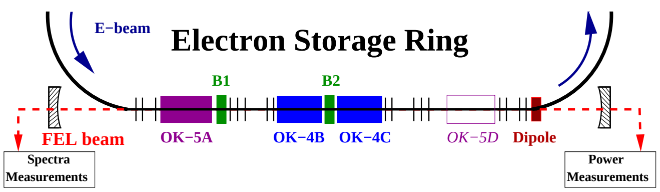

FIG. 1. (color online). The schematic layout of the FEL undulators for two-color lasing. The upstream helical OK-5A undulator is tuned to lase around 720 nm, while the downstream two-undulator OK-4 optical klystron is tuned to lase around 360 nm. Two bunchers $B1$ and $B2$ are used to control the two-color lasing.

To enable lasing in two distinct wavelength regions, a set of dual-band, multilayer dielectric FEL mirrors were specially developed with two highly reflective wavelength bands centered around 720 nm and 360 nm [40]. After conditioning new mirrors using undulator radiation, the FEL cavity round-trip loss was measured. In the IR region, the relatively flat wavelength band useful for robust FEL lasing is from 670 to 739 nm with the measured round trip loss between 0.15% and 0.30%. In contrast, the high reflectivity band in UV is narrower, from 350 to 374 nm, with the measured round trip loss between 1.2% and 3.0%. Due to synchrotron radiation induced mirror degradation, the cavity loss is dominated by absorption in the dielectric coating, with a small contribution from transmission which is estimated to be 1×10^{-4} in IR and 4×10^{-5} in UV per mirror.

Since the electron beam is used as the shared gain medium, it is imperative to keep the net FEL gains at two wavelengths close to each other during the lasing process. The challenge of matching FEL gains of the planar and helical undulators is realized by using the following three methods. First, the lasing wavelengths of two sets of undulators are properly matched to mirror's high-reflectivity bands. For a given electron beam current, OK-5A undulator has a relatively low gain due to poor transverse overlap between the electron and FEL beams in this undulator which is located about 10 meters upstream from the center of the optical cavity. The lower gain of OK-5A is partly compensated by operating it at an infrared wavelength (λ_1) around 720 nm where the optical cavity loss is lower. With a much higher gain, the optical klystron OK-4 is chosen to lase at an ultraviolet wavelength (λ_2) around 360 nm where the cavity loss is higher. Second, the gain of the OK-4 optical klystron is further reduced by adjusting buncher $B2$ (Fig. 1) to move the FEL lasing wavelength to the edge of the optical klystron's gain spectrum so that the radiation from the downstream OK-4C provides destructive interference to the radiation from upstream OK-4B for electrons of certain energy [41]. Third, the FEL cavity detune, i.e. the time synchronization between the electron and FEL beams, can be adjusted by changing the electron beam revolution frequency. The cavity detune changes the FEL gain by different amounts for two lasing processes. Using these techniques, reasonably good matching of the net gains of OK-4 and OK-5 undulators can be realized for two-color lasing.

All FEL measurements reported in this Letter were conducted using a single-bunch, 500 MeV electron beam in the Duke storage ring. The FEL was operated in the quasi continuous-wave mode with a small RF detune. The FEL spectra were measured using two spectrometers with wavelength ranges 477–1146 nm and 220–447 nm, respectively. Using band-pass filters, the extracted FEL power in each color was measured using a photodiode, while the total extracted power was measured using a thermal powermeter. For two-color lasing with a 16 mA beam (Fig. 4), the electron bunch length was about 70 ps (rms) (peak current 33 A) before lasing, and about 150 ps (rms) (peak current 15 A) in steady lasing. For each mirror, the maximum total extracted power was about 7 mW and the maximum outcoupled UV power is about 0.3 mW.

For this two-color FEL, wavelength tuning and power control can be realized using a set of tuning knobs with some of them having multiple functions. The main wavelength tuning knobs are undulator strengths $K_{\text{OK-5}}$ for IR lasing (λ_1) and $K_{\text{OK-4}}$ for UV lasing (λ_2). As an optical klystron, the OK-4 lasing wavelength can be fine-tuned using $B2$ buncher by adjusting the optical phase slippage N_{B2}. For a pair of given lasing wavelengths, the FEL gain, and therefore the power, can be controlled using three main knobs: (1) N_{B2} (a shared wavelength knob) to manipulate the OK-4 lasing power; (2) N_{B1}, the optical phase slippage provided by buncher $B1$ to control the OK-5 lasing power; and (3) the cavity detune knob to effectively regulate the power distribution between the two lasing beams. In addition, the lasing wavelength and power are also sensitive to optical cavity alignment and electron beam orbits in the undulators, which is kept unchanged whenever possible in our studies.

For many important research applications using a two-color laser, it is essential to have the flexibility to independently adjust the lasing wavelength of one color without changing the other lasing wavelength. Experiments were carried out to tune either λ_1 or λ_2 in a relatively large range. As shown in Fig. 2, while fixing the UV lasing wavelength (360.05 ± 0.04 nm), the IR lasing wavelength λ_1 is tuned from 734.88 to 674.92 nm with a step size of about 5 nm by decreasing $K_{\text{OK-5}}$, realizing a wavelength tuning range $\Delta\lambda_1 = 60.0$ nm. During the tuning, bunchers $B1$ and $B2$ and cavity detune are used to maintain simultaneous two-color lasing and to provide fine adjustments of lasing wavelengths. Fixing the IR wavelength (720.00 ± 0.09 nm), the UV lasing wavelength λ_2 can be tuned from 374.09 to 349.98 nm by varying $K_{\text{OK-4}}$. The resultant tuning range of UV lasing is $\Delta\lambda_2 = 24.1$ nm.

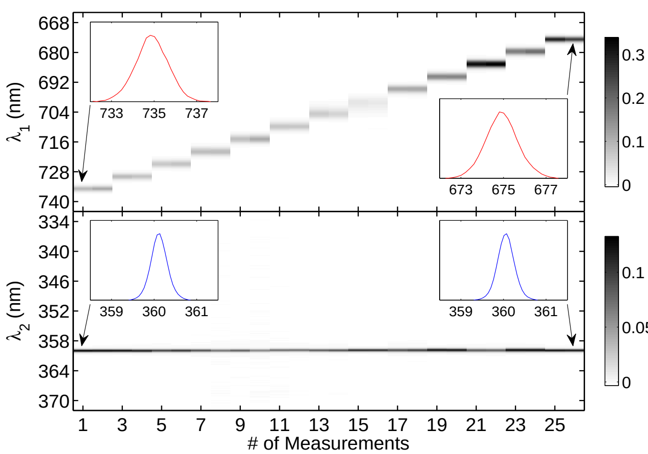

FIG. 2. (color online). Measured spectra with IR lasing wavelength λ_1 tuned from 734.88 to 674.92 nm by varying the OK-5A undulator setting. In the meantime, the UV lasing wavelength λ_2 is held steady with the centers of the measured spectra kept in a small range, 360.05 ± 0.04 nm. A total of 13 pairs of spectra were measured while the electron beam current was kept between 15.8 and 16.5 mA.

This two-color FEL can also produce simultaneous lasing with two harmonically related wavelengths, $\lambda_1 = 2\lambda_2$. Wavelength tuning of harmonic lasing is accomplished by simultaneously adjusting $K_{\text{OK-4}}$ and $K_{\text{OK-5}}$ according to Eq. (1), with fine tuning of λ_2 provided by buncher $B2$. Buncher $B1$ and cavity detune are used to maintain simultaneous lasing with reasonable intensity in both colors. In Fig. 3, the OK-5 lasing wavelength is increased from 704 to 740 nm by increasing $K_{\text{OK-5}}$ from 3.179 to 3.279. For each wavelength, $K_{\text{OK-4}}$ is increased accordingly (from 3.325 to 3.430) to shift the OK-4 lasing wavelength from 352 to 370 nm. Compared to independent wavelength adjustments, the harmonic lasing tuning ranges ($\Delta\lambda_1 = 36$ nm and $\Delta\lambda_2 = 18$ nm) are narrower. This is caused by two main factors: (1) the dual-band mirror has a narrower high-reflectivity band in UV than in IR, and (2) these high-reflectivity bands are not perfectly matched with a second harmonic relationship. In Fig. 3, ten selected pairs of measured lasing spectra are shown to demonstrate the second harmonic relationship—the measured frequency difference, $\delta\lambda = \lambda_1/2 - \lambda_2$, varied from -0.09 to 0.08 nm, is much smaller than the average rms spectral widths $\sigma_{\lambda_1} = 1.34$ nm and $\sigma_{\lambda_2} = 0.31$ nm. These measurements demonstrate that this two-color FEL is capable of producing harmonic lasing in a wide wavelength range, limited by the overlap of the high-reflectivity bands of the FEL mirrors.

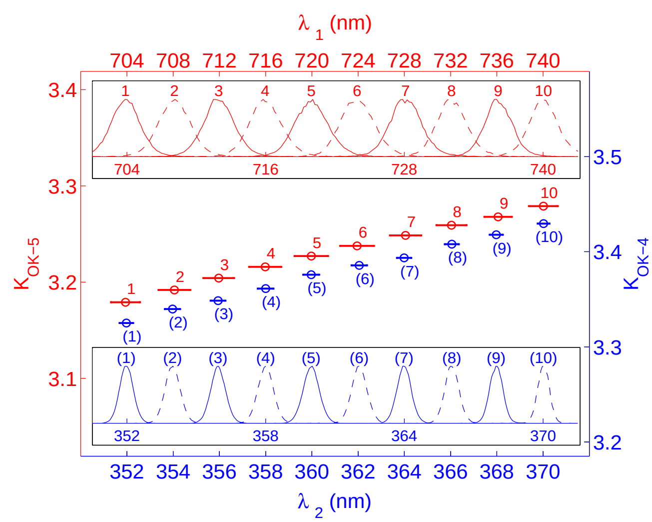

FIG. 3. (color online). Wavelength tuning of harmonic two-color lasing ($\lambda_2 \approx \lambda_1/2$). The center wavelengths (circles) and rms widths (horizontal bars) of ten pairs of measured spectra are shown as a function of the undulator strength $K_{\text{OK-5}}$ or $K_{\text{OK-4}}$. These spectra with substantial lasing intensities in both colors are selected from 72 pairs of lasing spectra measured while keeping the electron beam current between 19.59 and 20.75 mA. The measured spectra with their maximum intensity scaled to unity (the odd ones in the solid curves and even ones in dashed curves) are displayed in the upper and lower insets for IR (λ_1) and UV (λ_2) lasing.

The storage ring FEL power is limited by the growth of electron beam energy spread due to FEL induced diffusion [42–46]. The maximum power radiated by the electron beam directly in FEL interaction can be expressed as

$$P_{\text{SRFEL}} \approx \alpha\, P_{\text{syn}} \frac{\sigma_{\text{FEL}}^2 - \sigma_0^2}{\sigma_{\text{FEL}}}, \tag{2}$$

where P_{syn} is the total synchrotron radiation power emitted by the electron beam in the entire storage ring, σ_{FEL}

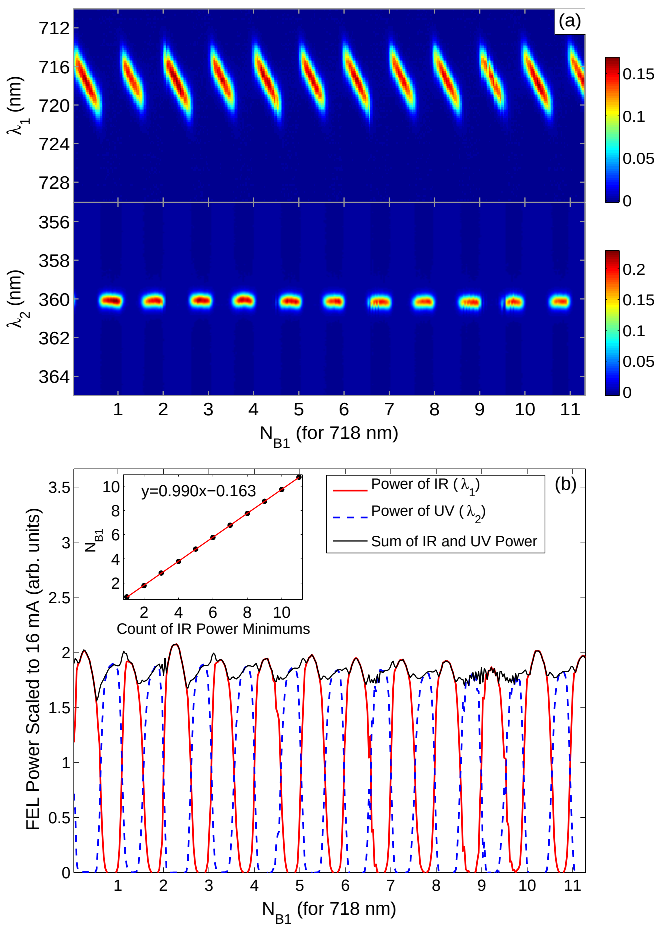

FIG. 4. (color online). Controlling two-color FEL power using N_{B1}. The beam current was maintained between 15.6 and 16.4 mA with top-off injection and buncher $B2$ setting was fixed ($N_{B2} = 0.60$ for 360 nm). (a) The measured spectra linearly scaled for a 16 mA beam. (b) The FEL power emitted directly by the electron beam for IR lasing (red solid), UV lasing power (blue dashed), and the sum of the two powers (black). In the insets, the N_{B1} values at the minimum IR power is plotted as a function of the count of the minimums, and a linear fit is used to determine the periodicity of power tuning.

and σ_0 are the electron beam's relative energy spread with FEL turned on and off, respectively, and α is a numerical factor of order unity which depends on the undulator configuration and FEL operation conditions. In steady state operation, this FEL power balances against the total cavity loss to sustain a much larger intracavity power inside a high-finesse cavity. It is interesting to investigate whether the total FEL power is subject to the same power limitation in two-color operation, and whether the FEL power distribution in two colors can be controlled.

In the two-color FEL power study, N_{B1} was chosen as the only tuning knob while keeping other operation parameters unchanged. As N_{B1} was varied, the lasing spectrum and the extracted FEL power of both colors were recorded simultaneously, while the electron beam current was kept steady using top-off injection. Two photodiodes used to measure the extracted power were cross-calibrated using Eq. (2) and the measured FEL-induced electron beam energy spread with single-color lasing, so that the measured extracted FEL power could be scaled to represent the FEL radiation power P_{SRFEL} in Eq. (2).

Figure 4 shows the measured FEL spectra in both colors as N_{B1} is varied from 0 to 11.3 (normalized using the central wavelength of IR lasing at 718 nm). In this process, lasing of each color is observed to be turned on/off about eleven times (see Fig. 4(a)). The FEL power emitted by the electron beam shows close to 100% modulation in Fig. 4(b), which indicates lasing at either color can completely dominate the FEL gain process, resulting in turning off the lasing of the other color. The values of N_{B1} for the minimal power of either color can be determined and fitted with the count of the minimums. The fit slope of 0.990 (with the IR power data) indicates that the FEL power for each color is periodically turned on/off as N_{B1} is advanced by unity. The total FEL power of the two-color lasing (rms variation of 4.5%) is roughly at the same level as the IR or UV lasing alone, indicating the two-color lasing is as efficient as and is subject to the same power limitation as the single-color lasing (see Eq. (2)). With two-color lasing, N_{B1} can be used to control the power partition among the two colors. With manual tuning of either N_{B1} or N_{B2} in a small range and occasional adjustment of the RF detune, the FEL power in each color can be well maintained. For example, when the UV power is about three times that of IR, the power stability is 5.2% (rms) for UV and 11% (rms) for IR in a 30-minute measurement.

In this Letter, we have reported the first operation of a two-color storage ring FEL using three undulators, a shared recirculating electron beam, and a common laser cavity. In this work, independent wavelength tuning of each color has been realized in a wide wavelength range limited by the FEL mirror's high-reflectivity bands. In particular, this two-color FEL can be operated at two harmonically related wavelengths ($\lambda_1 = 2\lambda_2$), which are also tunable. Two-color lasing has a similar efficiency to single-color lasing as demonstrated by having a similar total power. Full control of the FEL power in each color has been demonstrated using a single optical phase delay knob (N_{B1}), and good power stability can be realized with active tuning.

Due to certain specific quasilinear mechanisms of saturation in storage ring FELs, microbunching in the electron beam for each FEL wavelength is very small. Therefore, like a linear system, the superposition of microbunching at different wavelengths is possible, which can lead to simultaneous multiple-color lasing by properly balancing the FEL gains of the different colors. In principle, with adequate numbers of undulators, the storage ring FEL is a versatile laser which can produce lasing at more than two wavelengths as supported by the high-reflectivity wavelength bands of the optical cavity.

Using Compton backscattering [47, 48] to up-shift the photon energy, the two-color FEL can be used to drive a gamma-ray beam with two distinct energies. This research is ongoing after the first production of two-color gamma-ray beams in the few MeV region. Another direction of future research is to extend the two-color FEL lasing continuously across the entire visible spectral range from near IR to near UV using mirrors with ultra-broadband dielectric coatings.

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