Selective amplification of the lower-frequency branch via stimulated super-radiance in a waveguided free electron laser oscillator driven by short electron bunches

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In this letter, we propose a mechanism to extend the spectral range of a waveguided free electron laser (FEL) oscillator driven by a rf LINAC toward significantly longer wavelengths without changing the undulator or accelerator design parameters. This mechanism involves selective amplification of a lower-frequency branch supported in a FEL due to the waveguide dispersion. Based on simulations performed for the terahertz FEL under construction at the Radboud University Nijmegen, we conclude that these long wavelengths can be efficiently amplified via stimulated super-radiance as the electron bunches are shorter than the radiation wavelength. © *2010 American Institute of Physics*. [doi:10.1063/1.3524220]

Over the past few decades, free electron laser (FEL) technology has made enormous progress and, these days, FELs are designed worldwide for many unique applications which previously have not been feasible. Terahertz radiation is very interesting for research, and the first tunable versatile terahertz sources have been realized based on the FEL concept (see, e.g., Ref. 1).

Most FELs are driven by a rf LINAC producing typically few picoseconds long electron bunches. For a terahertz FEL employing a rf LINAC, strong spontaneous emission (SE) is expected during the FEL start-up at wavelengths longer than the size of the electron bunch. Such emission is known as super-radiance (SR), which implies that electrons emit light in phase and that the optical power scales as the squared number of electrons.[2] The SR regime in FELs provides the most efficient way to convert electron kinetic energy into optical energy.

The relatively long wavelengths of the terahertz radiation demand the use of a waveguide to minimize diffraction losses and to optimize the overlap between electron bunch and optical beam. For waveguided FELs, synchronism implies that two resonant frequencies, f^+ and f^- ($f^+ > f^-$), are possible. Due to the waveguide dispersion, an optical pulse at frequency f^+ propagates faster than the electron bunch and another one propagates slower. Investigations into coupling/competition between these branches have previously been reported.[3–14] Of relevance here is that it was demonstrated that for a waveguided FEL employing narrow electron bunches, the conventional FEL gain for the f^- branch is small when it is located far from the cut-off frequency and when the difference between f^+ and f^- is larger than a gain bandwidth.

The extension of the wavelength range is of importance for any light source because it allows new applications. Normally, such an extension for FEL requires costly changes in design parameters of an undulator or an electron accelerator. In this letter, we demonstrate a possibility for a short-pulse waveguided FEL to produce powerful coherent light at the frequencies of the f^- branch. The light amplification occurs due to the stimulated super-radiance which starts playing a significant role in the FEL operation at light wavelengths longer than the electron bunch longitudinal size. This enables elongation of the FEL spectral range toward significantly longer wavelengths with no changes in both the undulator and the electron accelerator design parameters. The results reported in this letter were obtained numerically for the Free electron Laser for Advanced spectroscopy and high-Resolution Experiments (FLARE) (Ref. 15), which is a new terahertz FEL-oscillator under construction at the Institute of Molecules and Materials of the Radboud University Nijmegen. Although FLARE is designed to generate terahertz light at the wavelengths of the f^+ branch, i.e., 0.1 mm (3 THz)–1.5 mm (0.2 THz), the mechanism suggested here enables reduction in the frequencies of the generated light down to ≈0.04 THz.

The FEL dynamics is simulated with a code based on a model similar to that reported in Refs. 16–19. Since this computational model does not employ any averaging over a ponderomotive or resonant wavelength, as is usually done for FELs operating at low slippage parameters, it enables simulation of the full FEL dynamics in the situation that the electron bunch length is comparable to the resonant wavelength, which is the case for FLARE. In order to reduce computational time, the code was parallelized using the MPI package.[20] Only the propagation of the E_{01}^{π} Hermite–Gaussian mode was considered in the model.[21] Space charge effects were assumed to be negligible and thus excluded from the simulation. Calculations were performed for instrument parameters as listed in Table I. In particular, the Gaussian electron bunches were described in the simulation by 100 quasiparticles.

The spectral energy density of the f^+ branch calculated at the first oscillator pass is negligible compared to f^- branch

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TABLE I. FLARE parameters used in the model.

Period of electron bunches	50.035 ns
Electron bunch duration	3 ps (std)
Electron bunch charge	200 pC
Electron beam energy	11 MeV
Undulator period	110 mm
Number of undulator periods	40
Undulator magnetic field	0.44 T
Optical cavity length	7.275 m
Round trip power losses	22%
Outcoupled power fraction	7%
Waveguide gap	10 mm
Rayleigh distance	200 cm
Resonant frequencies, f^+/f^-	188.4 GHz/54.5 GHz

[Fig. 1(a)]. This is because the SE is largest at the wavelengths longer than the electron bunch length. For light amplification at the next round trip, the optical pulse must overlap a subsequent electron bunch at the undulator entrance. Since the electron bunches are much shorter than the optical pulses, the gain of the stimulated emission as well as the outcoupled power depends on the position at which overlap occurs. This position can be varied by changing the cavity length using the upstream mirror. For a favorable overlap over the whole length of the interaction region, the electron bunch should merge with the rear edge of the f^- pulse at the entrance of the undulator. Then, due to the negative slippage occurring for the f^- branch, the electron bunch will leave the interaction region while overlapping with the front edge of the pulse. Since FLARE is initially designed to amplify the f^+ branch, the cavity length of 7.5 m must be reduced to 7.275 m enabling electron bunch interaction with the f^- optical pulse.

The calculated detuning curve, i.e., the average output energy as a function of cavity detuning, is presented in Fig. 2 and shows a periodic structure of spikes. The doubled period of spikes is ≈5.7 mm, which corresponds to k_z of the resonant f^- frequency. In a very early experiment with a millimeter-FEL in 1989, using a six period undulator and a microtron as electron source, detuning curves were observed with similar features as in Fig. 2 but with both branches being amplified.[22] However, in the approach presented here, we predict the selective amplification of the lower-frequency branch [Fig. 1(b)].

In general, the growth of optical energy in the FELs operating in the small-signal regime can be presented as[2]

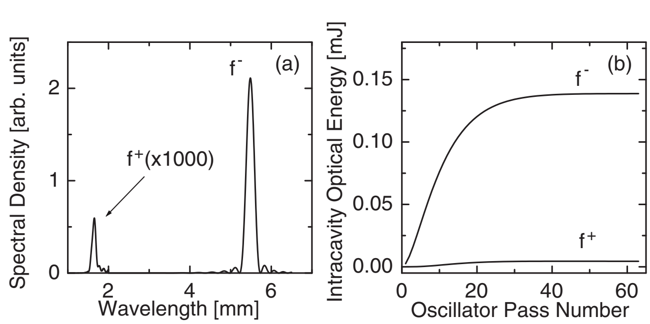

FIG. 1. (a) Relative spectral energy density after the first round trip. (b) Optical intracavity energy of two frequency branches at different oscillator passes. The cavity length of 7.275 m was detuned by $\delta L = 55.125$ mm.

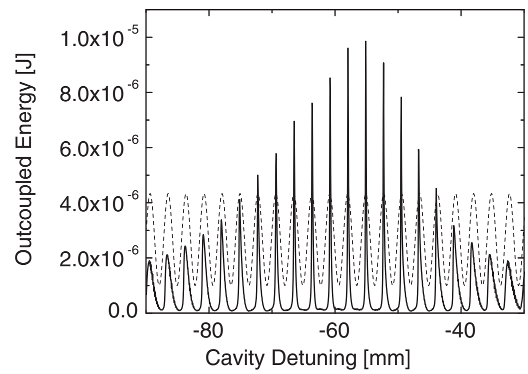

FIG. 2. Detuning curve is shown by the solid line. The initial cavity length is 7.275 m. Dotted curve presents $\cos(2\delta L k_z)$ dependence where $k_z = \sqrt{(2\pi f^-/c)^2 - (\pi/g)^2}$, where g is the waveguide gap.

$$\Delta W = \alpha_{\rm CSTE} W_{\rm in} + W_{\rm SE} + \alpha_{\rm STSR}\sqrt{W_{\rm in}}\cos\phi, \qquad (1)$$

where $W_{\rm in}$ is the input optical energy and ϕ is the electron bunch phase relative to the radiation mode. The conventional stimulated emission (CSTE) [the first term in Eq. (1)], which is linearly proportional to $W_{\rm in}$, is a general feature for all FELs and usually the dominant mechanism for light amplification. However, the CSTE gain of the f^- branch is expected to be negligible for FLARE. Indeed, the shape of the calculated detuning curve with the prominent spikes (Fig. 2) is remarkably different from conventional detuning curves showing a single peak (see, e.g., Ref. 23). The SE [the second term in Eq. (1)], in contrast to the CSTE, does not depend on the stored optical field in the cavity and is only determined by the profile of the electron bunch. The SE is most significant for the prebunched and short electron bunch FELs. The stimulated SR (STSR) presented in Eq. (1) by the third term was initially predicted theoretically[24] and subsequently observed experimentally.[25] The STSR is proportional to the optical field, i.e., the square root of the energy, and means that radiation can be amplified by a cw electron beam prebunched at the radiation frequency or at its subharmonic.[2] It is similar to the CSTE with a difference being that the CSTE occurs due to the coherent emission of the electron beam that is bunched on the scale of the resonant wavelength by the stored optical field in the cavity. It is important to note that the electron bunches of FLARE upon injection into the undulator are shorter than the wavelength of the resonant f^- frequency, therefore, it possesses features of the prebunched FELs as well. In order to conclude that STSR is indeed responsible for the light amplification in FLARE, two distinct features of the STSR should be verified: (1) the optical energy must scale as $\cos\phi$, and (2) it must be proportional to the square root of the input energy. The dependency on phase is obvious from Fig. 2, i.e., when $\delta L = \pi m / k_z$ (m is an integer) the electron bunch is injected in phase with the stored optical field resulting in light amplification. However, for other cavity detuning values the phase is not preserved at successive oscillator passes, which leads to the dips in the detuning curve. In order to verify the second feature of the STSR, the increment of total optical energy was calculated over one oscillator pass for different initial spectral density distributions. Such distributions were considered to have the same shape as the SE but different peak intensities. The results of the calculations performed at $\delta L = 55.125$ mm (Fig.

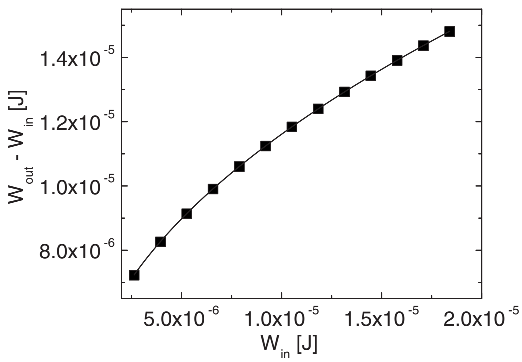

FIG. 3. The solid squares show growth of optical energy vs different W_{in} calculated for one oscillator pass when the cavity length was detuned by $\delta L = 55.125$ mm. The solid curve is defined in Eq. (2).

3), where the detuning curve shows the spike, are well described by the following dependence:

$$\Delta W = 2.63 \times 10^{-6} + 2.84 \times 10^{-3}\sqrt{W_{in}}, \quad (2)$$

where the optical energy is expressed in joule units. Equation (2) implies that the term linearly proportional to W_{in} is negligible. This corroborates our suggestion that the power growth of the f^- branch of FLARE is due to the STSR, which dominates over the CSTE.

In this paper, we have demonstrated that due to the combination of narrow electron bunches and a waveguided FEL, it is possible to selectively amplify the lower-frequency branch. For FLARE, it enables us to stretch the wavelength region by more than a factor of 3 without changing the design parameters of both the undulator and the electron accelerator. The method reported here is valid for other waveguided FELs driven by rf LINAC producing electron bunches shorter than the resonant wavelength.

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