GAIN DETERIORATION AT PARTICULAR WAVELENGTHS IN A PARTIALLY WAVEGUIDED FEL

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Abstract

At ELBE certain wavelengths within the working range of the FIR-FEL have been found to be inaccessible. The FEL either completely stops lasing or shows marked drop-outs in the observed optical spectra. The reason of this behaviour is sought in the use of a partial waveguide through the undulator to the downstream mirror combined with free optical propagation to the upstream mirror.

The light pulse from the upstream mirror couples into the lowest transverse mode of the waveguide with minor contributions of other modes. The light generated in the gain process, however, is distributed over some of these modes and experiences dispersion over the waveguided propagation length. At the exit of the waveguide the different modes recombine with certain phase shifts. Depending on the amount of phase shift and the mode composition of the light a gain drop or even inversion is possible if a major part of the stimulated emission is out of phase to the primary beam. This work attempts to compute the mode distribution of the stimulated light emission and to translate this into a prediction of those wavelengths where the gain is markedly reduced by destructive interference of different modes.

INTRODUCTION

At Forschungszentrum Dresden-Rossendorf, Germany, the radiation source ELBE (Electron Linac with high Brilliance and low Emittance) operates on the basis of a superconducting linear accelerator for electron energies up to 40 MeV with an average beam current of 1 mA in quasi continuous wave (cw) mode. The electron linac serves as a driver to generate several kinds of secondary radiation and particle beams. Two free-electron lasers generate radiation in the mid and far infrared for a very large field of applications reaching from semiconductor physics to biology.

The first FEL to become operational at ELBE was the mid-IR FEL [1] using two undulators with 27.3 mm period. With the available beam energies it covers a wavelength range from 3—24 µm. To extend the wavelength range into the far-IR a second FEL with a 100 mm period [2] undulator was installed. It now provides laser light from 20—250 µm. After first lasing in August, 2006 it is in routine user operation since fall, 2006.

The ELBE FIR-FEL uses a partial waveguide spanning from near the undulator entrance to the downstream mirror. The interior height was chosen to 10 mm. In horizontal direction the waveguide is wide enough to allow essentially free propagation. Thus, an overmoded parallel-plate waveguide is formed which shows low losses for the principal mode.

The downstream mirror was placed as a cylindrical mirror inside the waveguide. On the upstream side the optical beam propagates freely through the focusing quadrupoles and the dipole to a toroidal mirror. To allow for a near-optimum out-coupling over the whole wavelength range the upstream mirror chamber is equipped with three interchangeable mirrors of identical curvature but with 2.0, 4.5 and 7.0 mm out-coupling holes. The horizontal curvature of all mirrors was chosen to correspond to a Rayleigh range of 180 cm. To optimize the coupling between the waveguide mode and the free propagation the vertical curvature radius of 361 cm of the upstream mirror nearly equals its distance from the waveguide entrance.

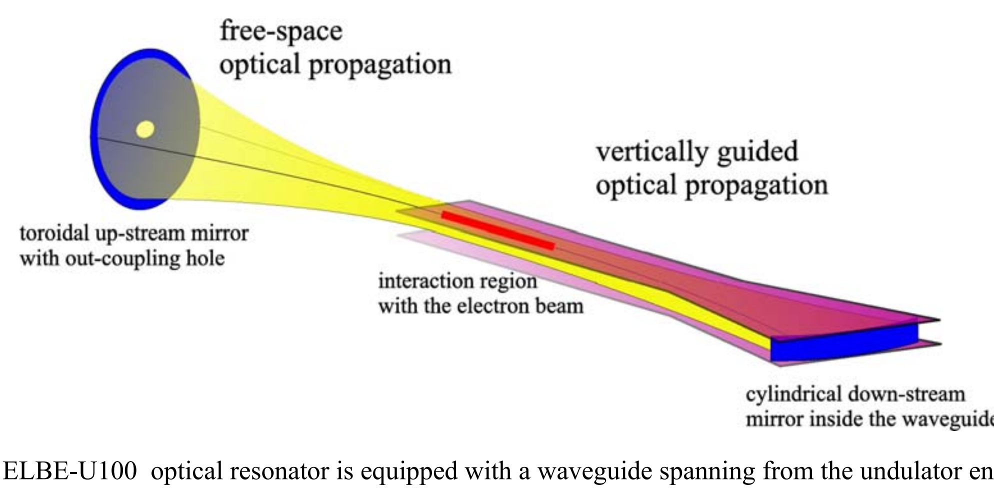

Figure 1: The ELBE-U100 optical resonator is equipped with a waveguide spanning from the undulator entrance to the downstream mirror with free-space optical propagation to the upstream mirror.

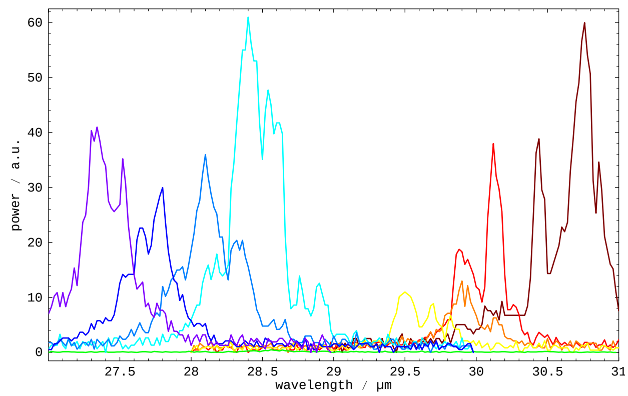

Figure 2: Measured spectra when tuning the wavelength by varying the undulator gap over the spectral gap around 29 µm.

WAVELENGTH GAPS

Certain wavelengths within the working range of the FIR-FEL have been found to be inaccessible. The FEL either completely stops lasing or shows marked drop-outs in the observed optical spectra. At lower beam energy or less optimized tuning the inaccessible gaps in the wavelength spectra widen but always stay at the same positions.

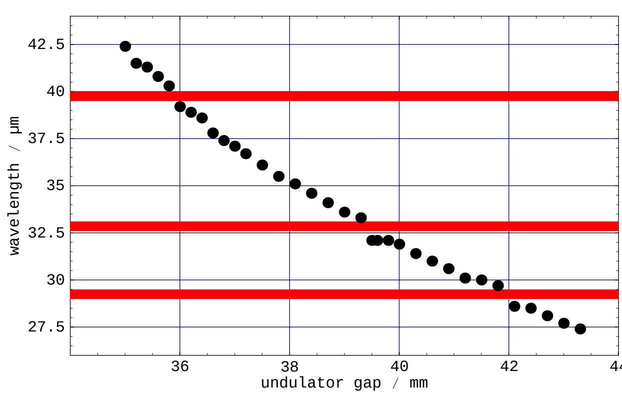

Figure 3: Wavelength versus undulator gap measured at 40 MeV electron beam energy. Even though the lasers is working for almost all settings of the undulator gap, some wavelengths are inaccessible (like 29 µm or 33 µm) which are shown with red stripes.

GAIN/LOSS MEASUREMENTS

To determine the origin of the gain deterioration we measured the round-trip optical losses and small-signal gain. For this, the electron beam was interrupted for 10µs after the FEL had reached saturation. The decay and re-buildup of the optical intensity were recorded with a fast detector and fitted with exponentials. Figure 4 shows a typical measured signal trace. The pink signal shows the electron beam current. The red trace is the measured optical power which clearly shows the bunch repetition frequency of 13 MHz, the blue trace is a filtered optical signal with the repetition frequency suppressed. The black lines denote the range of interest used for fitting the exponentials. Gain and loss data measured at 40 MeV beam energy are summarized in Figure 5.

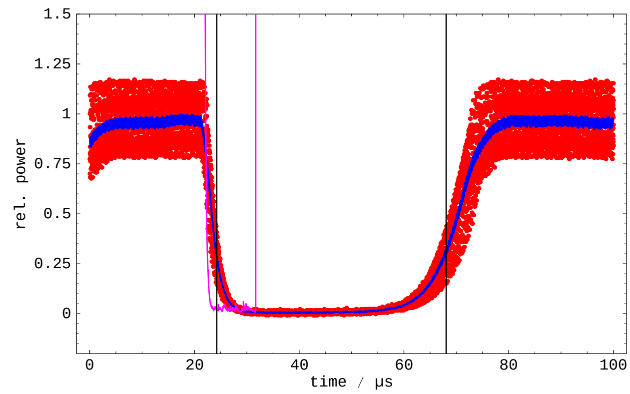

Figure 4: Measurement data for determination of the round-trip gain and cavity losses.

GAIN DETERIORATION MODEL

Very similar to the approach published in [3] we attribute the phenomenon to a particular combination of transverse waveguide-eigenmodes which compose the optical mode of the FEL. Dependant on the composition the intensity profile on the out-coupling mirror could be altered which would lead to a different out-coupling fraction. Any marked changes here, though, would clearly show in the optical quality of the resonator. From the data of Figure 5 it can be seen that besides some stochastical fluctuations the round-trip optical losses show no clear signature near the denoted wavelength gaps. This rules out any pure optical effect which would do nothing more but reduce the Q of the optical resonator.

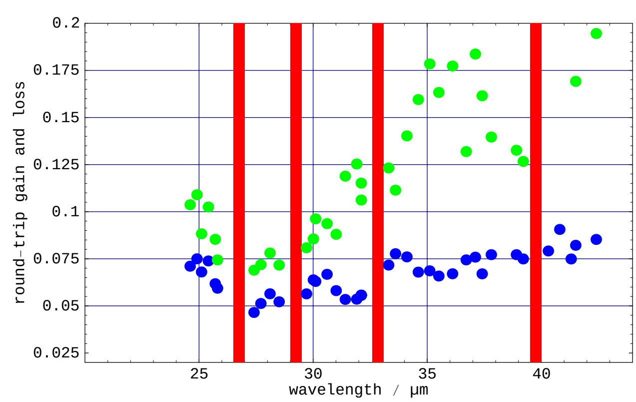

Figure 5: Cavity round-trip loss (blue) and small-signal gain (green) recorded at 40 MeV beam energy. The red stripes denote inaccessible wavelength ranges.

In contrast, we find that a reduction of the gain at particular wavelengths is the main origin of the inaccessibility of certain wavelengths. This gain drop is only poorly visible in Figure 5 as the figure only includes data points for which a reasonable optical power was recorded. However, it was very clearly visible in the scope traces like the one of Figure 4. Near the gapsthe break in the optical intensity drastically lengthened with the decay time staying approximately constant. It also seems that the exponential rise-time pictured in Figure 5 draws a somewhat incomplete picture. The duration of the recorded break in some cases was much longer than it should be if the rise would immediately with the return of the electron beam current start from the residual optical intensity.

From these measurements we conclude that the main reason for the wavelength gaps is a gain reduction which can be explained as follows. The incident light in the undulator causes a density modulation of the electron beam which is proportional to the total intensity of all modes. Because the electron beam is small compared to the optical mode size the light from the stimulated FEL emission populates essentially all odd low-order transverse modes of the waveguide with all the modes initially being in phase to each other. Due to their different phase velocity the higher-order modes experience a phase shift with respect to the fundamental mode. If after one round-trip the higher-order mode light is by π off-phase it reduces the optical field in the interaction region which corresponds to a negative gain.

The total waveguided pathlength at ELBE amounts to 15.85 m. Over this travel at a wavelength of 29.8 μm the fundamental and the 7th and the third and fifth transverse modes are just opposite phase to each other which explaines the very prominent gap at this wavelength.

CONCLUSIONS

With newly measured data we were able to gain some insight into the origin of the gain deterioration effect. While the proposed mechanism explaines the most pronounced wavelength gaps correctly further work is required to fully and in detail understand the effect.

REFERENCES

[1] P. Michel, P. Evtushenko, U. Lehnert, T. Dekorsy, F. Gabriel, E. Grosse, M. Helm, M. Krenz, W. Seidel, D. Wohlfarth, A. Wolf, R. Wünsch, First Lasing at the ELBE mid-IR FEL, 26th International Free Electron Laser Conference FEL 2004, Trieste, Italy

[2] E. Grosse, U. Lehnert, P. Michel, R. Schlenk, W. Seidel, A. Wolf, U. Willkommen, U. D. Wohlfarth, R. Wünsch, A Far-Infrared FEL for the Radiation Source ELBE, 27th Free Electron Laser Conference FEL 2005, Palo Alto, USA

[3] R. Prazeres, F. Glotin, J.-M. Ortega, 30th Free Electron Laser Conference FEL 2008, Gyeongju, Korea