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TITLE: FREQUENCY LOCKING IN COUPLED FREE ELECTRON LASERS

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FREQUENCY LOCKING IN COUPLED FREE ELECTRON LASERS

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Abstract

The application of optical phased arrays to obtain high output power, beam agility, and large equivalent output aperture has received considerable interest. In this paper, we investigate the scaling of free electron lasers using the phased array concept.

Introduction

The idea of using optical phased arrays to obtain high output power, beam agility, and large equivalent output aperture has received considerable interest. An optical phased array contains a laser array, which provides an array of frequency locked laser beams, and a telescope array, which phases the laser beams so that they combine constructively in one spot in the far field. An advantage of such a device is that the optical components and the lasers in the array need only be of a size that can be constructed with current technology. Therefore, one should not encounter any new problems involving fabrication and damage resistance of materials. The coherent combination of the beams causes the whole device to act as one coherent source. Consequently, we expect a smaller focal volume, and a higher power density in the far field, than is the case with randomly phased lasers. Whether this can be achieved in practice depends on our ability to frequency lock the laser beams to one another, and our ability to phase the laser beams with the telescope array, so that they combine constructively at the target.

There are several schemes for phase locking an array of lasers. A master oscillator and power amplifier (MOPA) array involves injecting into an array of laser amplifiers, radiation from a master laser. As long as the amplifiers are operated below their oscillation threshold, their output will be frequency locked to the master laser. In order that the laser beams add constructively at the target, the telescope array must ensure that the optical path lengths of the laser beams, from the master laser to the target, differ by an integer number of wavelength for a single frequency array or be equal for a multi-frequency array. In a phase conjugate MOPA (PC MOPA), the optical path length compensation is performed by nonlinear phase conjugation. The third scheme for a phased optical array involves injection locking an array of laser oscillators to a common master laser. Finally, there is a scheme that uses coupled resonators.

The FEL may be well suited for phased array applications because of the lack of gain medium perturbations. An FEL operates in a very quiet environment compared to, for instance, a chemical laser which often experiences appreciable optical beam distortion due to the presence of shock waves, chemical reactions, and turbulent gas flow. Our code simulations show that the pulse to pulse phase drift in an FEL is nearly constant (Fig. 1).

For the FEL we choose the MOPA array configuration shown in Fig. 2. Our scheme is basically a master oscillator driving a linear chain of amplifiers, producing several output beams of equal intensities. The output of the master oscillator-preamplifier section is a train of laser pulses that is sufficiently intense to saturate the power amplifiers. Each power amplifier is designed so that it doubles the intensity of an input pulse. Scrappers positioned after each power amplifier outcouples 50% of the laser intensity. In general, the outcoupled energy is determined by the gain in the power amplifier. The output of the entire array is several closely packed frequency locked laser beams. Figure 2 depicts a four-beam array. In principle, there is no limit to the number of power amplifiers, and hence to the number of laser beams, in an array. Figure 3 depicts in detail, a power amplifier module. Essential to the success of our scheme are the optics and control mechanisms for packing and equalizing the optical path distances traveled by the beams. An example of the beam control optics is shown in Fig. 4.

An estimation of the achievable output power from the above array may be obtained from the following example. Let us assume a master oscillator-preamplifier output of 7.2 Gw at a wavelength of $1.005 \mu\text{m}$. The wiggler in each power amplifier has a parabolic taper, with a wavelength that varies from 3.535 cm to 2.050 cm. The wiggler length is 15.70 m and the magnetic flux is 4125 gauss. Also for the power amplifier, we assume an electron beam current of 500 amps with $\gamma = 184.19$, and a beam radius of 1.3 mm. With this power amplifier, the intensity of an input 7.2 Gw pulse will be doubled to 14.4 Gw, with an efficiency of approximately 15%. The output of our hypothetical array will consist of four beams each consisting of a train of 7.2 Gw pulses. Assuming that each micropulse is 20 ps, and that there are 1000 micropulses per macropulse, we have 576 joules/macropulse from the four beams. By operating the accelerator at 180 Hz, we get 0.1 Mw of average output laser power from the entire device. The power density on a target would depend on the actual phase telescope array design.

Since our scheme uses an array of power amplifiers, the output beams are automatically frequency locked. There remains, however, the question of optical path length compensation to properly phase the output of the entire array. To answer this question, we need to know if the fluctuations present in our device are sufficiently small to be correctable by conventional phase array techniques. The fluctuations will be mainly due to differences in the power amplifiers. In particular, the electron bunches driving the power amplifiers are most likely to have an energy fluctuations. This will lead to differences in the gain among the amplifiers, which in turn will lead to differences in the gain-induced phase shift among the different laser beams. Figure 5a depicts the phase imparted on a laser field after propagation through an amplifier module. Note that for an energy spread of 2%, the phase shift difference is only $\lambda/25$. Better yet, the absolute phase shift due to the gain is less than $\lambda/15$, which is negligible. Figure 5b depicts the gain in an FEL amplifier module as a function of electron energy. Note that the change in gain is negligible if the electron energy bunch fluctuation is kept to less than 1%. Hence, both phase and gain fluctuations due to electron bunch energy fluctuations are within required tolerances.

In summary, we have described a scheme that uses the phased array concept to scale free electron lasers. The basic features are: the use of rf linacs as power amplifiers, the use of a linear chain of power amplifiers to produce an array of frequency locked laser beams, and the use of conventional phase telescope array techniques to phase the laser beams so that constructive combination occurs at the target. Further work on phased FEL arrays involves the design of proof of principle experiments, and investigation of variations to the basic scheme described in this paper (see for example Fig. 6).

FIGURE CAPTIONS

- Fig. 1: Pulse to pulse wavefront variation in an FEL. The dimensions x and y refer to two orthogonal directions in the plane of the optical beam cross section. The different curves correspond to the different passes made in a FEL resonator.
- Fig. 2: A scheme for an FEL phased optical array.
- Fig. 3: An amplifier module in the FEL phase array shown in Fig. 2. For graphical simplicity, we have represented the mirrors by lenses.
- Fig. 4: Example of beam control optics using a fixed reference with rigid metering trusses.
- Fig. 5: (a) Phase and (b) gain fluctuations due to electron bunch energy spread.
- Fig. 6: FEL phase array with circulating optical pulses. The smaller FEL ring oscillator is for mode control and laser start-up.

OPTICAL PHASE

FIG 4.

(a)

(b)

Fig. 6