Optics & Laser Technology 46 (2013) 111–126

Contents lists available at SciVerse ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Review

High-power free-electron lasers–technology and future applications

Yehoshua Socol *

Falcon Analytics, POB 82, Netanya 42100, Israel

ARTICLE INFO

Article history:
Received 29 March 2012
Received in revised form
11 June 2012
Accepted 29 June 2012
Available online 22 August 2012

Keywords:
Free electron laser
Technology
Applications

ABSTRACT

Free-electron laser (FEL) is an all-electric, high-power, high beam-quality source of coherent radiation, tunable – unlike other laser sources – at any wavelength within wide spectral region from hard X-rays to far-IR and beyond. After the initial push in the framework of the "Star Wars" program, the FEL technology benefited from decades of R&D and scientific applications. Currently, there are clear signs that the FEL technology reached maturity, enabling real-world applications. E.g., successful and unexpectedly smooth commissioning of the world-first X-ray FEL in 2010 increased in one blow by more than an order of magnitude ($40\times$) wavelength region available by FEL technology and thus demonstrated that the theoretical predictions just keep true in real machines. Experience of ordering turn-key electron beamlines from commercial companies is a further demonstration of the FEL technology maturity. Moreover, successful commissioning of the world-first multi-turn energy-recovery linac demonstrated feasibility of reducing FEL size, cost and power consumption by probably an order of magnitude in respect to previous configurations, opening way to applications, previously considered as non-feasible. This review takes engineer-oriented approach to discuss the FEL technology issues, keeping in mind applications in the fields of military and aerospace, next generation semiconductor lithography, photo-chemistry and isotope separation.

Contents

* Tel.: +972 50 661 9622.
E-mail address: socol@FalconAnalytics.com

0030-3992/$ - see front matter
http://dx.doi.org/10.1016/j.optlastec.2012.06.040

1. Introduction

Free-electron laser (FEL) is a unique laser technology, enabling creation of tunable high-power sources. The "heart" of FEL is so called *undulator* (or *wiggler*) – a magnetic structure, creating space-alternating – but constant in time – magnetic field (see Fig. 1). High-energy electrons (delivered by an electron accelerator) wiggle due to the space-alternating magnetic field, i.e. oscillate in the transverse (to the propagation) direction, and high-frequency electromagnetic radiation is emitted. Therefore FEL is all-electric device in the meaning that, unlike high-power chemical lasers, it uses only electricity as the primary power.

The term "Free-electron laser" was coined by Madey [1], who proposed FEL in its present concept. The work on devices, based on similar principles, had been already performed for decades. Phillips [2] reported device he called "ubitron", which was essentially a microwave tube with undulator. The undulator, however, was built (and undulator radiation experimentally studied) back in 1951 by Motz [3], and even earlier in 1947 proposed by Ginzburg [4,5].

Free-electron laser was first demonstrated in 1976 [6] in the infrared region. This demonstration triggered vivid interest worldwide. Very soon the military concluded, that FEL is probably the only technology, capable of achieving power levels and optical beam quality estimated to counter intercontinental ballistic missiles. Already in 1978, DARPA (US Defense Advanced Research Projects Agency) issued call for proposals, and the scientific community response included conceptual design from Los Alamos for a 10 MW FEL [7]. Further in 1983, the field was granted relatively high funds in the framework of the Strategic Defense Initiative (SDI) in the US, and also around the globe.

The practical results of the centralized military-oriented effort were discouraging. Until 1998, only about 10 W of electromagnetic power – instead of the planed 10 MW – were available [7]. The primary reason was that the then-available electron accelerators were unable to provide *e*-beams of sufficient quality. With the end of the Cold War, SDI was discontinued, and so was with massive investment in high-power FELs (it seems appropriate to mention in this context that though SDI failed even to approach its design goals, it posed a great political and economic challenge to the USSR and is considered by many experts to be important factor contributing to the collapse of the latter and thus ending the Cold War. If so we have an example how a tactical fiasco can turn into a strategic victory).

The momentum gained by the FEL science and technology was far not totally lost. The first international FEL conference was organized in 1979, and has been held on yearly basis ever since. Back in 1977, Vinokurov and Skrinsky suggested a modification of FEL – optical klystron [8], which enabled in 1983 to achieve lasing in visible [9] and in 1989 — in the UV spectral region [10]. The important achievements in the accelerator and FEL technology during 1980s enabled to build first user centers, exploiting the unique capabilities of FELs to produce high-brightness optical beams in the IR-to-UV spectral range.

During the two decades of roughly 1990–2010, FEL research installations and user facilities were built all over the world (the number of active FEL facilities is presently estimated as about 40). Concurrently there was a steady accumulating of advances in all the three sub-fields of the FEL technology—electron injection, main electron acceleration, and FEL interaction and optics (the division is somewhat arbitrary, but logical and widely mentioned). The short-wave limit of the electromagnetic spectrum available to the FEL technology gradually expanded from initial IR in 1976 to the hard

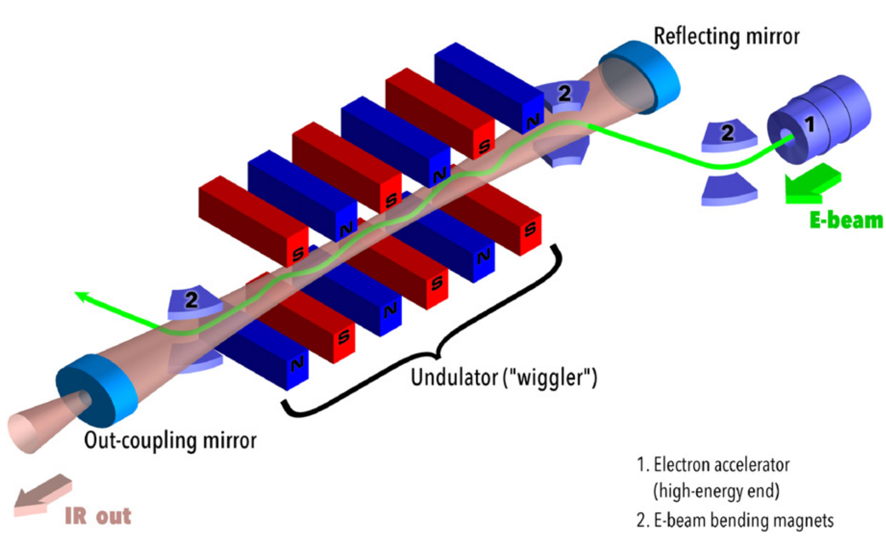

Fig. 1. General IR–FEL lay-out.