FEMTOSECOND Yb-DOPED FIBER LASER SYSTEM AT 1 μm OF WAVELENGTH WITH 100-nm BANDWIDTH AND VARIABLE PULSE STRUCTURE FOR ACCELERATOR DIAGNOSTICS

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Abstract

Laser-based diagnostic systems play an increasingly important role in accelerator diagnostics in, for instance, electron bunch length measurements. To date, the laser system of choice for electro-optic experiments has been the Ti:sapphire laser, providing several nanojoules of pulse energies at fixed a repetition rate, which is not well suited to the bunch structure of accelerator facilities such as FLASH. Limited long-term stability and operability of Ti:sapphire systems are significant drawbacks for a continuously running measurement system requiring minimal maintenance and maximum uptime. We propose fiber lasers as a promising alternative with significant advantages. Gating of the pulse train to match the bunch profile is simple with fiber-coupled modulators, in contrast to bulk modulators needed for Ti:sapphire lasers. An in-line fiber amplifier can boost the power, such that a constant pulse energy is maintained regardless of the chosen pulse pattern. Significantly, these lasers offer excellent robustness at a fraction of the cost of a Ti:sapphire laser and occupy a fraction of the optical table space.

INTRODUCTION

There is much progress and scientific excitement on new light sources, which will provide higher brightness and shorter temporal structures, with promise for broad impact in a large number of disciplines, from condensed matter physics and nanotechnology, to materials science and biology. Among the emerging key requirements, is to determine the electron bunch length and temporal structure for free electron laser based machines, such as FLASH to ensure best possible lasing performance. Various optical techniques based on electro-optic effects have been implemented and these methods have delivered promising results as non-invasive means to characterize the electron bunch structure [1, 2].

However, none of these diagnostic methods have yet evolved into a routine tool. One of the leading reasons is the complexity, limited robustness and flexibility of the laser systems in use. Most commonly, the laser of choice is the Ti:sapphire laser. Although these laser oscillators offer the best performance in some aspects (such as the pulse duration and spectral bandwidth), they have significant shortcomings in other aspects of significance for these applications. The repetition rate is fixed and most commonly set to a value between 70 and 120 MHz, with pulse energies of ~ 5 nJ. If more energy is required, an amplified Ti:sapphire system has to be used, which in turn is limited to a kHz-level repetition rate. Such a laser system is a vastly more complicated tool and occupies nearly an entire optical table. In terms of the repetition rate, neither the laser oscillator nor the amplified system are particularly suited for free-electron laser or synchrotron based light sources: A superconducting machine such as FLASH, requires a repetition rate of 1 MHz if every pulse in the bunch is to be sampled. The bunch pattern typically consists of hundreds of pulses with 1 MHz spacing, with the overall pattern being repeated at 1-5 Hz. Gating of the pulse train of a Ti:sapphire laser is possible with electro-optic modulators, but these modulators are lossy, require high voltages to operate and need to be precisely aligned with respect to the laser beam to maintain a contrast ratio of ~ 25 dB. Subsequent amplification, to restore the pulse energy, requires the addition of an amplifier, which is a major modification of the experimental setup.

Mode-locked fiber laser systems present a promising alternative, as the pulse pattern can be engineered to match the machine requirements through gating and subsequent amplification. Even plain laboratory-constructed fiber lasers without professional packaging have been shown to work without interruption for several months and longer. Rapid progress has been made with Yb-fiber laser oscillators operating at 1 μm in the past few years. A new mode-locking regime exploiting self-similar pulse propagation has been demonstrated [3] and these lasers now routinely generate sub-100 fs pulses with over 5 nJ of energy at repetition rates of 30-60 MHz [4]. A suitable harmonic of the repetition rate of the oscillator can be locked to an external reference by modulating a piezo-driven fiber stretcher, which is part of the cavity. Thus, the pulse train produced by the oscillator is synchronized to the facility clock. The pulse train can be gated to produce any desired pattern, thereby matching the electron bunch structure exactly. Both fiber-couped acousto-optic modulators (AOM) and electro-optic modulators (EOM) are available at this wavelength, therefore gating is simple to implement. The on/off contrast ratio for a fiber-coupled AOM is extremely high (at least 50 dB) and in practice limited by the driving electronics. Fiber-coupled EOMs offer the convenience of requiring less than 5 V for switching and the contrast can be as high as 35 dB. Following pulse gating, the reduced optical power can be boosted with an in-line fiber amplifier. Small signal gain for a single pas through a fiber amplifier is as high as 30-40 dB, an extraordinarily high value in comparison to typical solid-state laser gain media. Pump light is provided by telecom-grade singlemode fiber-coupled diode lasers, which are low-cost and extremely compact. Thus, subsequent amplification is practical and easy to implement, in sharp contrast to Ti:sapphire amplifiers. In other words, if so desired, the individual pulse energy can be kept the same value, regardless of the particular bunch pattern. Using in-core pumping, up to 1 W of power can easily be generated (corresponding to several 1μJ at 1 MHz repetition rate). Higher power levels (several watts) can also be implemented with double-clad gain fibers and multimode pump diodes. In practice, the biggest challenge is the limitation to peak power and pulse energy set by the strong nonlinear effects that occur in fibers. In this regards, boosting the individual pulse energy up to 100 nJ is relatively easily achieved with a design that optimizes the nonlinear and dispersive effects. This level of pulse energy is sufficient for several of the diagnostic techniques. At the higher end, pulse energies as high as 100μJ have been obtained from fiber amplifiers.

Mode-locking of a fiber laser is initiated by a mechanism (a saturable absorber) providing lower loss (hence, higher net gain) for a pulse than for continuous wave (cw) radiation, leading to pulse formation from intra-cavity noise once the laser reaches a certain intracavity power. Once the pulses are shortened, the laser dynamics are dominated by an interplay of group velocity dispersion (different frequencies have different speeds) and Kerr nonlinearity (the refractive index depends on intensity), leading to the formation of soliton-like pulses, which intrinsically balance dispersion and nonlinearity [5]. As the gain has finite bandwidth, the generated pulses need to be stabilized by the saturable absorber. Thus, at the simplest possible level, short-pulse laser dynamics can be described by four processes: laser gain, saturable absorption, Kerr nonlinearity, and dispersion. In fiber lasers, the fiber assumes multiple roles, providing nonlinear and dispersive effects that dictate the soliton-like pulse shaping mechanism. The Yb-doped fiber segments form the gain medium, pumped conveniently by low-cost, fiber-coupled, 980-nm diode lasers.

MODE-LOCKED YTTERBIUM FIBER LASERS

Our experimental setup is compact, occupying a 30cmx45cm optical board, including the pump lasers, and thus able to fit into a small case (see figure 2). A unidirectional ring cavity (Figure 1) is chosen for self-starting operation. We use a 60 cm-long, highly doped Yb fiber (N.A., 0.12; core diameter, 6 μm). The Yb fiber is pumped at 980 nm by a laser diode with a maximum power of 500 mW coupled into single-mode fiber. The pump light is delivered to the gain fiber by a wavelength-division multiplexing coupler. A pair of diffraction gratings compensate for the normal group velocity dispersion (GVD) of the fiber. Mode-locked operation is initiated and stabilized by nonlinear polarization rotation, which is implemented with in-line polarization controllers (alternatively, bulk waveplates can be used). Following the gratings, the pulse is coupled back into fiber, where it traverses approximately 2 m of single-mode fiber, which is wrapped around a piezo material, acting as a fiber stretcher, before reaching the Yb-fiber, completing the cavity loop. The total lengths of the fiber and free-space sections of the cavity are adjusted such that the repetition rate (54 MHz) is an exact sub-harmonic (24^{th}) of the reference frequency (1300 MHz) for the FLASH facility. The output is taken directly from the polarization ejection port, placed immediately after the fiber section and prior to the gratings. A schematic of the laser is shown in Figure 1.

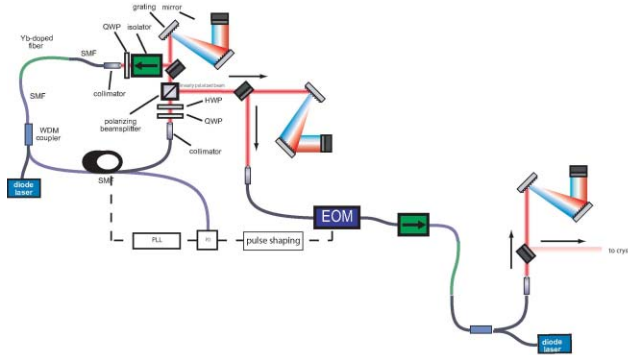

Figure 1: Schematic of the Yb-doped fiber laser setup.

Figure 2: Photograph of the laser and external dechirping gratings in its transportation case.

The laser generates positively chirped pulses, which are dechirped with a grating pair external to the cavity. The positive chirp is intentionally overcompensated and the pulses are coupled into the fiber amplifier with a negative chirp. The amount of this negative chirp is adjusted such that the pulses are chirp-free, maximizing their peak power, at a point within the fiber amplifier, where the power is highest. This way, the dominant nonlinear effect, self-phase modulation, is maximized, resulting in broadening of the pulse spectrum. The spectrum of the pulses after the amplifier have a full-width at half-maximum of ~ 100 nm. The spectral flatness shown in figure 3 is satisfac-

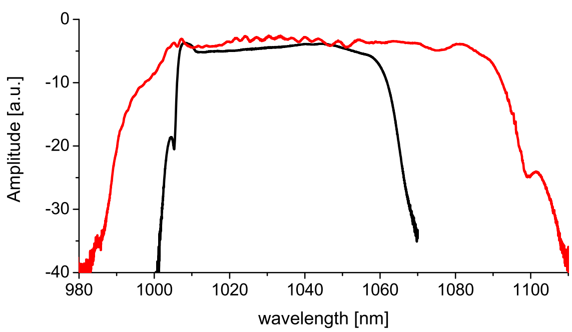

Figure 3: Optical spectrum obtained directly out of the laser (black) and after amplification and spectral broadening (red).

tory, which can be improved further with proper control of higher-order dispersion.

ELECTRO-OPTICAL EXPERIMENTS AT 1 μM WAVELENGTH - SIMULATIONS

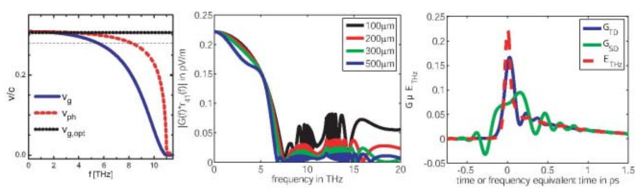

Figure 4: left: group velocity of optical radiation at 1 μm (dotted line) and 800 nm (dashed line) and group and phase velocity at THz frequencies for GaP middle: crystal response function for GaP including group velocity mismatch and frequency dependence of the electro-optic coefficient r_{41} right: Simulated ideal signal expected for a 70 fs long, 0.5 nC electron bunch passing the crystal in 4 mm distance (red); signal expected with temporal decoding(blue) and spectral decoding (green).

It is also important to consider the interaction of the laser pulses with the THz radiation obtained from the electron bunch. In this regards, a Yb-fiber laser system operating at 1μm of central wavelength is advantegous over Ti:sapphire lasers at 800 nm of central wavelength. The limiting factors in terms of resolution and signal-to-noise ratio in electro-optic experiments are the phonon resonances of the crystals used and the phase matching between THz radiation and the laser pulse. This limits the allowable crystal thickness and hence the signal-to-noise ratio. The group velocity of the pulse at 1 μm wavelength is almost exactly equal to the group velocity of radiation up to 7 THz, which is the point at which resonance effects start to play a significant role (left panel of figure 4). A simulated transfer function of the crystal is numerally obtained (middle panel of figure 4. We conclude that a crystal thickness up to 500 μm can be tolerated without significant degradation of the crystal response. This is about a factor of five more than that is possible for 800 nm, hence a similar level of improvement can be expected for the signal-to-noise performance, assuming otherwise equal conditions. The right panel of figure 4 shows the expected signal for a 70 fs long, 0.5 nC charge electron bunch passing the crystal at a distance of 4 mm. The expected signal using the temporal decoding measurement scheme is shown in blue with a duration of 138 fs, whereas the signal to be expected from a spectral decoding measurement is shown in green in the same figure. This assumes a laser pulse with 100 nm bandwidth chirped to 2 ps. For details regarding the measurement techniques, see [1, 6].

CONCLUSIONS

We propose fiber lasers as an attractive alternative laser system for non-invasive electron beam diagnostics. The fiber laser approach offers significant advantages over the traditional choice of Ti:sapphire lasers. Fiber lasers are very compact in size, cost significant less and have better long-term stability and operatability. In addition, the ability to generate a pulse train that matches the bunch profile exact, in a way that it can be electronically reconfigured, while maintaining a nearly fixed individual energy appear to be significant advantages. Experimentally, we have constructed a ytterbium-doped fiber laser with a configurable pulse pattern (using a fiber-coupled electro-optic modulator), implementing an intra-cavity fiber stretcher for locking a harmonic of the repetition to the facility. The laser generates nearly 100-fs pulses, which are amplified and spectrally broadened such that the spectral bandwidth is 100 nm and 350-mW of average power (limited by available pump power), corresponding to a pulse energy of ~ 6.5 nJ. This combination of parameters makes this laser nearly ideal for electro-optic measurements of all bunches within a FLASH macropulse. Simulations indicate that the wavelength of 1 μm is excellently suited to electro-optic experiments, in terms of phase matching with the THz radiation.

REFERENCES

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