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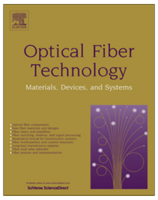

Invited Paper

Invited paper: Short pulse generation in mid-IR fiber lasers

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ABSTRACT

Mode-locked fiber lasers emitting short pulses of light at wavelengths of 2 μm and longer are reviewed. Rare-earth doped silica and fluoride fiber lasers operating in the mode-locked regime in the mid-IR (2–5 μm) have attracted attention due to their usefulness to spectroscopy, nonlinear optics, laser surgery, remote sensing and ranging to name a few. While silica fiber lasers are fundamentally limited to emission wavelengths below 2.2 μm, fluoride fiber lasers can reach to nearly 4 μm. The relative infancy of fluoride fibers as compared to silica fibers means the field has work to do to translate the mode-locking techniques to systems beyond 2 μm. However, with the recent demonstration of a stable, mode-locked 3 μm fiber laser, the possibility of achieving high performance 3 μm class mode-locked fiber lasers looks promising.

1. Introduction

Mode-locked fiber lasers in the near infrared (0.7–2 μm) have led to breakthrough experiments in optical, atomic, and molecular physics [1–4] and found application in industrial [5] and medical settings [6]. These laser systems, which can emit high peak-power ultrashort pulses (<30 fs) at high repetition rates (1 MHz–1 GHz), offer robust and efficient operation with diffraction-limited beam quality. All-fiber versions of these lasers allow researchers to use these lasers in a turnkey fashion since there are no free-space components and thus no alignment issues. This fact has allowed mode-locked fiber lasers to expand to fields outside of laser research, and has enabled non-experts in other fields to use these lasers as a tool rather than a research project. An example of this is corrective laser eye surgery, which is now a routinely performed medical procedure that relies on tissue ablation via a mode-locked fiber laser [7,8].

Recently there has been much interest in translating these high performance laser sources into the mid-IR spectral range (2–5 μm). In this wavelength range, many important molecules have strong fundamental ro-vibrational absorption lines. The interaction between the molecule and the mid-IR photon can be orders of magnitude stronger than that of near-IR photons, which typically interact with the molecule via overtone or combination absorption. This allows mid-IR sources to achieve sensitive detection (ppb, ppt) of trace molecules [9]. Alternatively a high power source emitting in this wavelength range can be used to shape materials such as plastics (C–H strongly absorbs at 3.2 μm) or human skin (H_2O strongly absorbs 3.0 μm) through ablation processes. Since mode-locked laser systems emit short high peak power pulses, they are ideal sources for materials shaping and processing applications. It has also been shown that carbonization (and thus scarring) of human tissue is minimized by using a laser source at the fundamental absorption of 3 μm, and even at 2 μm the carbonization is much lower than at 1.55 μm [10]. Likewise, for broadband, simultaneous detection of trace amounts of molecules in a sample one needs a broad bandwidth source [11]. A mode-locked system in the mid-IR combined with a supercontinuum stage is an ideal source for this application. Ultimately, these systems can be turned into self-referenced frequency combs to enable ultra-sensitive, simultaneous, absolute frequency spectroscopy of a wide range of molecules.

In this Review, we examine the state of the art of mode-locked fiber lasers emitting at wavelengths of 2 μm and longer. Section 2 briefly covers the performance of near-IR mode-locked fiber lasers. This is followed by a discussion of silica fiber and mid-IR compatible fluoride fiber (Section 3). In Section 4, we review 2-μm-class mode-locked fiber lasers and in Section 5, we cover mode-locked fiber lasers operating around 3 μm in fluoride glass. Finally, Section 6 provides a prospectus on the future of long wavelength mode-locked fiber lasers.

2. Performance of Near-IR mode-locked fiber lasers

Mode-locked fiber lasers in the near-IR rely on silica (SiO_2) fibers doped with rare-earth elements such as Ytterbium (Yb^{3+}),

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Erbium (Er^{3+}), Thulium (Tm^{3+}), and Holmium (Ho^{3+}). In certain cases, these fibers are co-doped with two of the rare-earths and an energy transfer process can take place between the ions. Each of these ions offers a unique laser emission in terms of central wavelength and bandwidth.

2.1. Ytterbium mode-locked fiber lasers

On the short wavelength side (1 μm), Yb^{3+} fiber lasers have been pushed to impressive performance levels in both continuous wave (cw) and mode-locked operation. CW Yb^{3+} lasers have now demonstrated 100 kW of average power [12], with a wall-plug efficiency of 35%. The quantum defect of these lasers is very low (slope efficiency ~90%) and the technological maturity of 980 nm diodes allows for high power pumping with high reliability. At these extreme average power levels, Yb^{3+} lasers become useful for directed energy weapons for defense systems. In a 2010 demonstration, Raytheon used a singlemode 32 kW Yb fiber laser system to destroy a drone from a distance of several kilometers [13].

Mode-locked Yb fiber lasers producing ultrashort pulses offer the potential for much higher peak power, albeit at lower average power. All-fiber mode-locked systems employing chirped-pulse amplification (CPA) have demonstrated nearly 4 GW of peak power [14]. For materials processing applications, ultrashort pulse systems are emerging as high performers relative to high average power systems. Using ultrashort pulses allows for cold ablation of the material, minimizing the collateral damage caused by excessive thermal loading [15].

Perhaps the most ambitious mode-locked Yb fiber laser system is the International Coherent Amplification Network [16], which is to be used for laser Wakefield particle acceleration [17]. The project aims to amplify (employing CPA) a Yb^{3+} mode-locked seed laser producing 30 fs pulses in up to 10,000 individual Yb^{3+} amplifiers and then coherently combine the ultrashort pulses to achieve 1–10 TW peak power. When focused, the peak intensity will be high enough to drive electrons relativistically and create high-energy particle acceleration with accelerations of 10–100 GeV/m.

2.2. Erbium mode-locked fiber lasers

Moving to a slightly longer wavelength, the Erbium ion doped into silica offers emission at 1550 nm, with approximately 100 nm bandwidth. As this wavelength range corresponds to the lowest transmission loss of silica fiber, the major contribution of Er^{3+} doped silica systems is the optical fiber amplifier [18] for telecommunications. Due to the adoption of this technology by the telecommunications industry, cheap, rugged components (i.e. pump diodes, splitter/couplers, wave division multiplexors, etc.) are widely available and creating mode-locked fiber lasers at this wavelength has become quite popular. Indeed, the first mode-locked optical frequency comb was creating using the Er^{3+} silica system [19]. Applications of the mode-locked Er^{3+}-doped silica fiber laser include spectroscopy [4], frequency standard transfer over fiber links [20], and laser eye surgery [21].

2.3. Mode-locked fiber lasers beyond 2 μm

Moving beyond 1550 nm, the Thulium ion provides gain centered at 1980 nm, with a large bandwidth of ~200 nm. Mode-locked Tm^{3+} doped silica fiber lasers have not yet found the high impact applications like the Yb^{3+} and Er^{3+} systems, but their future is very bright. Recently, a frequency comb based on this gain medium was demonstrated with spectral coverage from 1050 to 2550 nm [22], enabling ultra-sensitive broadband spectroscopy of molecules beyond 2 μm.

Yb, Er, and Tm have each received a significant amount of research attention and accordingly have achieved high performance and been commercialized. As is shown in Fig. 1, these mode-locked fiber laser systems have been pushed nearly to the fundamental limit (determined by the gain bandwidth) in terms of ultrashort pulse generation [23–28]. Mode-locked systems beyond 2 μm, including Tm–Ho, Ho, and the mid-IR transitions of Er and Ho are relatively new and have a lot of room for pulse width reduction. At 2 μm silica fiber begins to exhibit increased loss and silica fiber components begin to exhibit reductions in performance. Going to even longer wavelengths near 3 μm, the silica glass has to be abandoned entirely. As will be discussed in the next section, lasing at these extremely long wavelengths can only be achieved in low phonon-energy glass fibers, such as the fluorides or chalcogenides.

3. Silica fiber vs fluoride fiber: the Multi-phonon edge

Moving beyond 2 μm emission, a significant, fundamental materials science challenge arises. The silica glass host that the rare-earth ions are doped into starts to inhibit radiative emission from excited states. This process, which leads to the so-called multi-phonon edge, occurs when the energy gap between the upper laser level and the lower laser level is equal to the energy of a few phonons in the host glass. The laser emission is essentially quenched as the non-radiative decay rate via phonons becomes greater than the radiative emission rate of photons.

The multi-phonon decay rate (W_{mp}) for a particular excited state of a rare-earth ion depends on the phonon energy of the glass host medium, and can be modeled by [29–31]:

$$W_{mp} = \beta(n(T) + 1)^p e^{-(\alpha\Delta E)}$$

where β and α are constants with units of cm^{-1}, $n(T)$ is the Bose–Einstein occupancy for a phonon mode of energy $\hbar\omega$, p is the number of phonons required to bridge the energy gap, and ΔE is the energy gap of the lasing transition. The decay rate is both temperature-dependent and exponentially dependent on the energy gap of the transition ΔE. As shown in Fig. 2, glasses with low phonon energy exhibit a multi-phonon edge at long wavelength (i.e. low photon energy). Alternatively, cooling the optical fiber (and thereby lowering the Bose–Einstein occupancy term) can reduce the multi-phonon decay rate.

Qualitatively, to achieve low phonon energies the host lattice needs to consist of heavy atoms that are bound together with bonds that display low spring constants (i.e. weakly bound). Chalcogenide and fluoride glass (i.e. soft glasses), in particular, exhibit low phonon energy and are chemically stable. In the chalcogenide family, phonon energies are typically 350–380 cm^{-1} [33], while in the fluorides they are typically 500–565 cm^{-1} [32]. One fluoride glass that has enjoyed particular success is the heavy metal fluoride known as ZBLAN: ZrF_4 (53 mol%)–BaF_2 (20 mol%)–LaF_3 (4 mol%)–AlF_3 (3 mol%)–NaF (20 mol%) [34,35]. The phonon energy in ZBLAN is 565 cm^{-1}, as compared to 1100 cm^{-1} in silica, and the glass matrix lends itself to rare-earth doping. The effect of the low phonon energy on the long wavelength transmission of the glass can be see in Fig. 3. With rare-earth ions doped into ZBLAN [36], the range of emission wavelengths can extend out to nearly 4 μm [37].

In the near-IR, mode-locked lasers have benefited immensely from silica fiber technology. While the development of this technology was driven by the rapid rise of fiber-based components for telecommunications at 1550 nm, robust, high performance components are now available across all of the useful rare-earth wavelengths in the near-IR. However, fluoride fiber technology has lagged significantly behind. The lower physical strength of

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