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Invited Paper

Advances in 2-μm Tm-doped mode-locked fiber lasers

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ABSTRACT

Over the last five years, the number of demonstrations of mode-locked thulium-doped fiber lasers with output wavelengths around 2 μm has increased rapidly. Mode-locked Tm-doped fiber lasers now provide pulse energies above 150 μJ and durations less than 30 fs (although not simultaneously). Applications for these sources are continuously being developed as they become commercially available and currently include medicine, environmental sensing, materials processing, and defense. A review of previously demonstrated mode-locked thulium-doped fiber lasers up to the state-of-the-art will be presented along with the aforementioned applications of these sources.

1. Introduction

Ultrafast pulsed sources are gaining interest due to the large number of applications requiring pulses with high peak powers and broad bandwidths. By producing extremely short pulses (down to a few cycles of the electric field) with correspondingly high peak powers, mode-locked lasers are perhaps the most versatile of available pulsed sources. These properties make them especially useful for nonlinear optics [1–3] and laser processing [4]. When stabilized, their clean temporal output pulse train corresponds to a well-defined frequency comb in the frequency domain, which can be useful for precise temporal and spectral measurements [5]. Other important applications include spectroscopy, medicine, and remote sensing.

Mode-locking occurs when numerous longitudinal modes of the laser cavity resonate in phase and interfere to create pulses at a repetition rate that is determined by the cavity length (or the longitudinal mode spacing Δf_{FSR}), as shown in Fig. 1 [6]. Due to the Fourier relationship between the time and frequency domain, a larger number of in-phase longitudinal modes (or a larger spectral bandwidth) will generate a shorter pulse duration. For a hyperbolic secant squared pulse, the time-bandwidth product (TBP), which is the product of the spectral bandwidth (Δf) and the temporal pulse duration (Δt), is limited to $\Delta t \Delta f \geqslant 0.315$ [7]. The TBP limit of 0.315 can only be achieved for an unchirped pulse with no phase difference between spectral components. For Gaussian pulses, this limit increases to 0.44 [6].

There are two approaches for initiating phase-locking of the cavity longitudinal modes: active mode-locking and passive mode-locking. Almost all reported demonstrations of mode-locked Tm-doped fiber lasers utilize passive mode-locking (since actively mode-locked sources utilize components that are not readily available). In passive mode-locking, a saturable absorption effect sets the phase of the longitudinal modes. This saturable absorption can be induced by actual absorption, as is the case for semiconductor saturable absorber mirrors (SESAMs), or by a nonlinear effect, such as the Kerr effect. These saturable absorption effects are fast (femtosecond to picosecond response times) and are automatically timed to the peak of the circulating pulse in the cavity, which allows for ultrashort pulses to be generated at a repetition rate determined by the cavity length [7–9].

The many advantages of fiber lasers, including compact size, immunity to external vibration and noise sources, stable alignment, high efficiency, clean optical surfaces for high-power operation, and single-mode operation up to kilowatt average power levels, can be exploited by using optical fiber to produce these mode-locked lasers [10]. The compact form of fiber lasers provides the ability to produce long cavity lengths in a small package. With an all-fiber configuration, there is no need for frequent alignment, unlike is often the case with free-space solid-state lasers. These benefits can help reduce the laser's susceptibility to external noise sources and the drift in output power. In addition, single-mode operation can be easily achieved, and the typically large overlap between the pump and signal modes allows for high efficiency, which is critical when scaling to high average powers.

Thulium-doped fiber lasers have a wide gain spectrum ranging from about 1.8 to 2.1 μm, depending on the composition of the host glass. Pulsed sources with a broad spectral bandwidth in this

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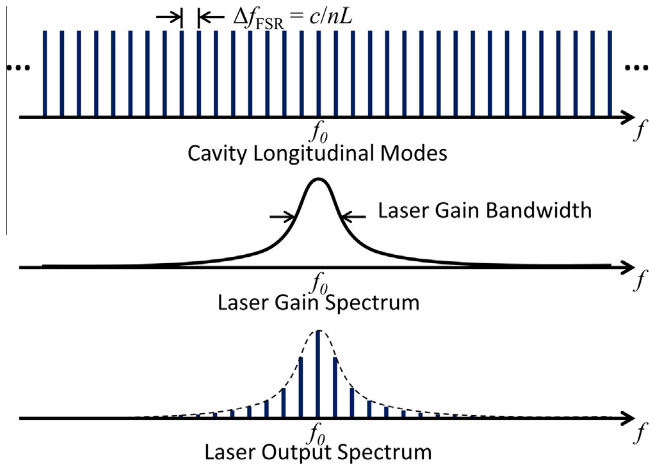

Fig. 1. Mode-locked output spectrum. The output spectrum of a mode-locked laser consists of a set of phase-locked longitudinal modes with an envelope determined by the laser gain spectrum (Δf_{FSR}: free-spectral range; c: speed of light in vacuum; n: refractive index of the cavity; L: round-trip cavity length; f_0: center frequency of the laser).

wavelength range have a growing number of applications, including nonlinear conversion to further into the mid-infrared (mid-IR), roughly 2–20 µm, for spectroscopy through either down conversion [11] or supercontinuum generation (SCG) [12–16], remote sensing [17], medicine [18–20], laser processing [21], dielectric laser-driven particle acceleration [22], and high-harmonic generation (HHG) [23]. The large gain spectrum makes generating ultrashort pulse durations that satisfy the requirements of these applications possible using Tm^{3+}as a dopant.

Furthermore, Tm^{3+} has proven to be an outstanding dopant for scaling average power, with a demonstration of over 1 kW of average power from a continuous-wave Tm-doped fiber laser system [24]. Since loss due to multi-phonon absorption in silica-based fibers quickly increases beyond 2 µm, this is the longest wavelengths that can support both broad gain bandwidth and high average power in these fibers. Utilizing doped silica gain fibers allows for the use of silica-based fiber components. Fiber lasers at longer wavelengths (>2.5 µm) typically use fluoride- [25] or chalcogenide-based [26] optical fibers, which generally require more complicated fabrication procedures [27] and utilize materials less robust to high peak and average powers. It is also worth mentioning that in high-power Tm-doped fiber lasers the use of conventional low-index polymer coatings for double-clad fibers when resonantly pumping with a low quantum defect may result in catastrophic damage of the cladding at low power, since the absorption at the pump wavelength can be large. An all-glass optical fiber composition would provide for a more robust laser system [24,28], although some polymers with reduced absorption in the 2-µm region may be adequate.

2. Oscillators

Initial demonstrations of mode-locked Tm-doped fibers lasers were reported around twenty years ago [29]. The telecommunications boom that started soon after shifted much of fiber research efforts to erbium and its emission band, and mode-locked Tm-doped fiber sources remained dormant until less than a decade ago. Recently, publications related to mode-locked Tm-doped fiber lasers have been increasing rapidly. This heightened interest stems largely from the increased importance of applications requiring mid-IR radiation and eye-safer wavelengths for sensing.

The initial mode-locked Tm-doped fiber oscillators utilized soliton mode-locking for pulse formation since typical silica fibers have anomalous dispersion in the 2-µm region. In soliton mode-locking, the nonlinear chirp induced by self-phase modulation (SPM) compensates the fiber's anomalous dispersion, allowing the pulse formed in the cavity to maintain its shape. These pulses require a delicate energy-mediated balance between the nonlinearity and the dispersion, which limits the pulse energy for a fundamental soliton to

$$E_p = \frac{2|\beta_2|}{\gamma T_0} \tag{1}$$

where β_2 is the group-velocity dispersion of the optical fiber mode, γ is the nonlinear coefficient of the optical fiber mode, and $T_0 = T_{FWHM}/1.76$ (where T_{FWHM} is the full-width pulse duration at half maximum) [30]. One way to better understand the balance between nonlinearity and dispersion is through characteristic lengths. The characteristic nonlinear length in the optical fiber can be described as

$$L_{NL} = 1/\gamma P_0 \tag{2}$$

where P_0 is the peak power of the pulse, and the characteristic length for dispersion, L_D, as

$$L_D = T_0^2/\beta_2 \tag{3}$$

when $L_{NL} < L_D$, nonlinearity dominates and causes pulse distortion. When $L_D < L_{NL}$, dispersion dominates and results in temporal broadening of the pulse. To form a fundamental soliton, L_{NL} and L_D must be equal [30,31].

Fig. 2 shows the evolution over the last 20 years of the shortest pulses reported in Tm-doped mode-locked fiber lasers. In 1995, the first demonstration of a mode-locked Tm-doped fiber laser produced one of the most flexible outputs, where sub-500-fs and 13.7-pJ soliton pulses with a 17.5-MHz repetition rate were obtained using nonlinear polarization evolution to achieve mode-locking [29]. The central wavelength was tunable across roughly 100 nm, from ~1.8 to 1.9 µm. This cavity configuration used a large number of free-space components as well to achieve

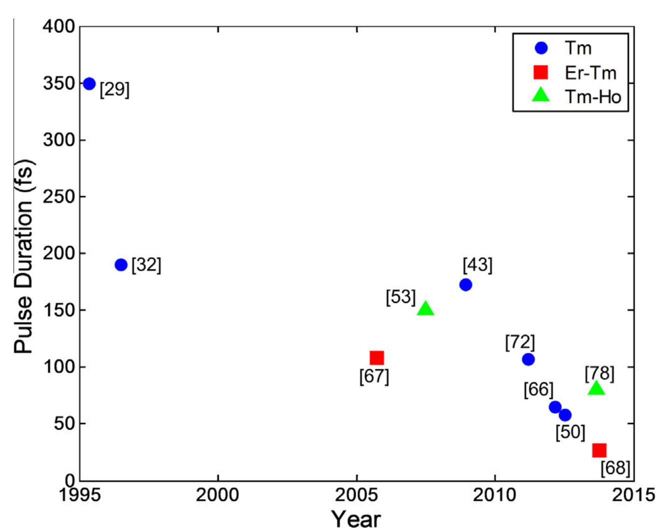

Fig. 2. Summary of shortest pulses durations observed over time in mode-locked Tm-doped fiber laser systems. The record minimum pulse duration for a mode-locked fiber laser system using either all Tm-doped fiber [29,32,43,50,66,72] (blue circle), Er-doped fiber oscillator and Tm-doped fiber amplifier [67,68] (red square), or Tm/Ho-doped fiber [53] (with Er-doped fiber oscillator [78]) (green triangle) is shown over time. The records currently stand at 58 fs [50], 27 fs [68], and 80 fs [78], respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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