A compact fiber laser is demonstrated with use of a Gires–Tournois compensator and a short length (2–4 cm-long) of highly doped ytterbium (Yb) fiber providing net anomalous group-velocity dispersion. With use of a novel semiconductor saturable absorber mirror based on GaInNAs structure, self-started 1.5-ps-pulse mode-locked operation was obtained at 1023 nm with a repetition rate of 95 MHz. A mode-locked Yb-doped fiber laser was developed without the use of any dispersion compensation technique. Overall group-velocity dispersion was minimized by using a short length of highly doped Yb fiber in a compact amplifying loop cavity. Self-started mode-locked operation was obtained in 980–1030-nm wavelength range with a fundamental repetition rate of 140 MHz. © 2004 Optical Society of America

1. Introduction

In past decades, diode-pumped solid-state lasers have dominated the area of tunable ultrashort-pulse light sources, offering not only extremely short optical pulses comprising several optical cycles but also broadband tunability. The recent, unprecedented growth of the telecommunications industry has resulted in the development of mature fiber technology and reliable and cost-effective components, which make suitably designed fiber lasers better contenders than conventional solid-state lasers. The broad fluorescence spectra make different fiber gain media attractive for tunable and ultrashort pulse sources. CW operation of a Nd:glass fiber laser was reported over a tuning range of 30-nm FWHM and more recently over 50-nm FWHM. For erbium-doped fiber lasers, tuning over 35 nm was achieved in an actively mode-locked system and over 50 nm in an additive-pulse mode-locked fiber soliton laser. For fiber lasers doped with thulium, which exhibits a particularly wide fluorescence spectrum, a tuning range as wide as 100 nm was demonstrated.

Ytterbium (Yb)-doped silica fiber having a broadband bandwidth, high optical conversion efficiency, and large saturation fluence offers an almost ideal gain medium for the generation and amplification of wavelength-tunable ultrashort optical pulses around 1 μm. An additional interesting feature of Yb-doped fiber lasers is that under certain conditions those lasers can operate in the 977-nm spectral band. This makes them a very attractive alternative to mode-locked Ti:sapphire lasers and as a master source for frequency doubling to achieve 488 nm and thus substitute bulky and inefficient argon-ion lasers. Despite significant attention to the development of practical user-friendly mode-locked sources operating in the region of 1 μm, there have been so far very few reports of successful demonstration of passively mode-locked fiber lasers, and there have been no reports on tunable fiber-based picosecond sources.

The main difficulty associated with short-pulse generation within Yb-doped fibers results from the high value of normal material dispersion for silica at wavelengths below 1.1 μm. Passively mode-locked fiber lasers that operate in the normal group-velocity dispersion (GVD) regime of silica glass (λ < 1.3 μm) may be operated only in the anomalous dispersion regime if dispersion compensators are introduced in the cavity, since it does not appear to be feasible to achieve overall anomalous dispersion of the fiber by exploiting the waveguide dispersion of ordinary single-mode fibers. With use of photonic crystal fibers it is possible to obtain soliton pulse operation at shorter wavelengths.

Usually, when it is necessary to offset the material dispersion, intracavity dispersion compensation can be preformed by use of prisms or grating pairs within all-fiber laser systems. The negative dispersion generated by a Gires–Tournois interferometer (GTI) or by chirped mirrors is sufficient for solid-state la-
sers to balance the dispersion of the laser rod. Nevertheless, because the GTI mirror is based on a multiple-beam concept, higher dispersion can, in principle, be generated through an increasing of the finesse of the interferometer. In practice, however, the resonance sharpness of the GTI affects strongly the usable bandwidth of the compensator. For this reason, in a typical fiber laser with a length of active medium of 1 m or longer and therefore a large net normal dispersion of the cavity, short pulse operation still requires dispersion compensators such as a grating pair, although bulk components add to the complexity and maintenance, require alignment, and increase the physical size of the system.

The advantage of the anomalous dispersion regime is that shorter pulses could be obtained when pulse shaping is assisted by soliton effects. Although soliton pulse shaping is a convenient method of short-pulse generation from fiber lasers, the soliton effects eventually limit pulse duration and energy. Alternatively, the so-called stretched-pulse technique was introduced for erbium-doped systems, minimizing soliton shaping. The principle of stretched-pulse mode locking uses cavity segments of large positive and large negative dispersion to introduce large changes of pulse width in the laser cavity and minimize nonlinear effects. Because silica fiber at ~1 μm has a high value of normal dispersion, the neodymium and Yb laser systems can be conveniently operated in the soliton-shaping regime. However, with large net normal dispersion mode-locking is difficult to initiate, and operation suffers from instability. For this reason, typical stretched-pulse lasers operate with small net normal group-velocity dispersion exploiting an appropriate compensation technique.

For coping with the difficulty in obtaining self-starting mode locking within a laser with a Fabry–Pérot geometry, semiconductor saturable-absorber mirrors (SESAM) have been conveniently used to ensure the self-starting character of the mode locking.

In this paper we experimentally investigate mode-locked Yb-doped fiber lasers. This paper is organized as follows. In Section 2 we present a mode-locked Yb fiber laser using an intracavity GTI for the generation of net anomalous GVD. The short-length highly doped Yb fiber provided a low value of net normal GVD that is compensated by a GTI mirror with a comparable amount of anomalous dispersion, while preserving an optical bandwidth sufficient for supporting picosecond pulses. In Section 3 a compact dispersion compensator-free mode-locked Yb-fiber laser is presented. To avoid the need for dispersion compensators, we built a short-length Yb-fiber laser. The few-centimeters-long highly doped Yb fiber and the short segment of the single-mode fiber are contained in the cavity, providing a low value of net normal GVD.

2. Mode-locked Ytterbium Fiber Laser with Use of a GTI Compensator

Dispersion compensation based on a GTI was studied with use of the laser setup shown in Fig. 1. The linear cavity is defined by the SESAM and the GTI reflector. The total length of the fiber within the cavity was 74 cm, including a 10% output coupler. The Yb-doped silica fiber (NA = 0.22; cutoff wavelength, ~910 nm) had an unsaturated fiber absorption at 977 nm of ~1900 dB/m. This Yb fiber was manufactured by Liekki Oy (Lohjo, Finland) with use of direct nanoparticle deposition technology.

The SESAM used, operating in the 940–1050-nm wavelength range, is based on a GaInNAs material known as a dilute nitride system. It was monolithically grown on an n-type GaAs (001) substrate and is similar to the long-wavelength SESAM described in Ref. 18. An antiresonant Fabry–Pérot structure of SESAMs is formed by the uncoated front surface and the highly reflecting AlAs/GaAs mirror stack. This absorber allowed us to reliably trap the pulse spectrum at the regime with anomalous GVD of the GTI.

The GTI we used was made with use of an electron beam evaporator. The GTI consists of bottom and top distributed Bragg reflectors (DBRs) with 10 and 4.5 pairs of SiO2/TiO2, respectively, spaced by a 0.7-μm-thick of SiO2. Calculated mirror reflectivities at 1023 nm are \( R = 0.9356 \) for the top DBR and \( R = 0.9989 \) for the bottom DBR. The GTI structure resonance was positioned near \( \lambda = 1022.8 \) nm, as seen from the reflectivity spectrum shown in Fig. 2. Al

![Fig. 1. Cavity configuration for a mode-locked Yb fiber laser with use of a GTI compensator.](image)

![Fig. 2. Measured reflectivity of the Gires–Tournois structure. A reflectivity dip at resonance is shown.](image)
though an ideal GTI is expected to have a flat power reflectance spectrum, there is a dip at resonance in the reflectance of the high-finesse GTI, owing to a reduced reflectivity of the bottom mirror. The resonant extra loss would push the lasing spectrum away from the anomalous GVD regime toward the GTI reflection maximum.\textsuperscript{19} To lock the pulse spectrum to the region of the anomalous GVD, we have used a SESAM with a large change in nonlinear reflectivity (up to 8%).\textsuperscript{18} With this absorber mirror, the decrease in cavity loss for short-pulse operation is higher than the loss penalty, owing to the dip in the GTI reflectivity at this wavelength (\textlesseq 1%). As a result, the mode-locked operation starts spontaneously at the wavelength range with the anomalous GVD and remains reliably trapped at this region.

The laser threshold for cw operation was \textasciitilde 15 mW. When the Yb-doped fiber length was \textasciitilde 2.5 cm, the central lasing wavelength was within the range of 1020–1030 nm. With shorter lengths of Yb fiber, the laser was operating at 980 nm. Self-started mode-locked operation at spectral range around \( \lambda = 1023 \) nm with an anomalous GVD was obtained for pump power above 40 mW with an output power up to \textasciitilde 1 mW. Figure 3 illustrates autocorrelations traces for the laser operating with a GTI reflector and with the GTI replaced with an ordinary highly reflective mirror. The pulse durations were 1.5 and 15.6 ps, respectively, assuming a Gaussian pulse shape. Comparison of the autocorrelations shows that the GTI provides significant compensation of the fiber dispersion. Implementing the GTI resulted in the pulse shortening factor of the order of 10. The time-bandwidth products without and with dispersion compensation by use of the GTI are 0.98 and 0.43, respectively, showing that the compensation results in the generation of transform-limited Gaussian pulses. The fundamental cavity frequency was 95 MHz.

Figure 4 shows the GTI reflectivity and the resultant GVD around the resonance and pulse spectra with the GTI and with a highly reflective mirror used instead of the GTI. The negative GVD generated by the GTI is approximately \textasciitilde 0.05 ps\(^2\) at the laser wavelength. The total dispersion in the cavity, including a double pass of the fiber segment and the GTI, was estimated to be \textasciitilde 0.01 \pm 0.005 ps\(^2\). This estimation shows that the total cavity dispersion corresponds to a small, net anomalous group-velocity dispersion. The uncertainty in the cavity dispersion relates to the problem of estimating the dispersion of the highly doped Yb fiber.

It is important to note that, using a SESAM with high contrast of nonlinear reflectivity, the operation in the negative GVD regime near \( \lambda = 1022.8 \) nm was possible without any wavelength-selective elements despite the reflectivity dip around the GTI resonant wavelength. Mode-locked operation occurs spontaneously at this wavelength for sufficient pumping power.

3. Short Length Mode-Locked Ytterbium Fiber Laser

To minimize dispersion induced by the fiber and thus avoid the need for any intracavity dispersion compensators, we built a short-length fiber laser using highly doped Yb fiber, as shown in Fig. 5. The laser could be operated with an even smaller cavity dispersion by

![Fig. 3. Autocorrelation traces for pulsed operation with and without GTI.](image)

![Fig. 4. Upper graph, GTI reflectivity near the resonant wavelength with calculated group-velocity dispersion; lower graph, pulse spectra with and without dispersion compensation.](image)

![Fig. 5. Amplifying-loop cavity configuration for a short-length stretched-pulse Yb-fiber laser.](image)
simple use of the fiber section of the cavity consisting of a gain fiber. However, in such a setup we would need to use bulk optics to pump the Yb fiber, to take the output using mirror splitter, etc. Therefore the laser loses its main advantage: compactness and robustness of the all-fiber configuration.

The linear cavity is defined by the amplifying fiber loop mirror and the semiconductor saturable absorber mirror. Placing the Yb fiber in the loop mirror allows us to keep the signal/pump wavelength-selective coupler and the output coupler external to the laser cavity and thus to reduce further the fiber segment of the laser cavity. The signal/pump wavelength-selective coupler and the loop mirror were made of fiber with a cutoff wavelength of ~910 nm. The fiber loop mirror was designed to couple ~20% of the power to the output. It should also be mentioned that the fiber coupler forming the loop mirror acts as a nearly symmetrical splitter at the pump wavelength of 915 nm; therefore the Yb fiber was pumped from both ends, providing near-uniform inversion.

The SESAM and the Yb-doped fiber used were the same as described in the previous section.

The laser threshold for cw operation was ~15 mW. Self-started mode-locked operation was obtained for pump power above 40 mW, with the output power up to ~1 mW. When the Yb-doped fiber length was short enough (~2 cm), the laser was operating at 980 nm. When the length of doped fiber was increased to 3–4 cm, the central lasing wavelength was shifted toward 1020–1030 nm, owing to the reabsorption of 980-nm emission, as shown in Fig. 6. Figure 7 illustrates autocorrelation traces for the lengths of the Yb fiber of 2.1 and 4.1 cm. It can be seen that a longer Yb fiber, i.e., a higher value of a normal GVD, results in a stronger pulse stretching. It is important to note that the pulse does not exhibit the pedestal, though the autocorrelations can not be fitted neither with a sech^2 nor a Gaussian profile. To compress the output pulses by removal of the positive temporal chirp, we have used an anomalous dispersive delay line.11 The experiments have shown that the chirp of the pulses is highly linear, resulting in an efficient pulse compression. These results will be presented in a future paper. The fundamental cavity frequency corresponds to the pulse repetition rate of 140 MHz, as seen from the scope trace in Fig. 8.

4. Conclusions

In conclusion, we have demonstrated mode-locked Yb-fiber laser operation in the normal and anomalous dispersion regime. To achieve the anomalous dispersion regime, we used a Gires–Tournois compensator in a short length cavity with a 2.5-cm highly doped Yb fiber. With use of a broadband semiconductor saturable absorber mirror based on GaInNAs, which has a large change in nonlinear reflectivity, self-started 1.5-ps pulse mode-locked operation was obtained at 1023 nm with a repetition rate of 95 MHz. Implementation of the GTI resulted in a pulse-shortening factor of the order of 10. Specially designed high-reflectivity Gires–Tournois mirrors have been proved to be attractive candidates for control-

---

**Fig. 6.** Output spectra from the mode-locked laser in the 980–1030-nm wavelength range, obtained with Yb fiber with lengths ranging from 2.1 to 4.1 cm.

**Fig. 7.** Autocorrelation traces for stretched pulse operation with lengths of Yb fiber of 2.1 and 4.1 cm.

**Fig. 8.** Stable pulse train at the fundamental cavity frequency of 140 MHz.
ling intracavity dispersion in fiber lasers. We believe that if we use a GTI with smaller resonant losses, we would be able to avoid the bandwidth limitation provided by the present device. With improved design, currently under preparation, we expect to generate broader pulse spectrum corresponding to sub-500-fs pulses.

In the normal dispersion regime, stable and self-starting pulse operation was obtained without applying any dispersion compensation technique. Overall normal group-velocity dispersion was minimized by use of a short length of highly doped Yb fiber in a compact amplifying loop cavity. With use of the same broadband semiconductor saturable absorber mirror based on the GaInNAs material system, self-started mode-locked operation was obtained in the 980–1030-nm wavelength range with a repetition rate of 140 MHz.

In the cavity using the loop mirror, the self-phase modulation was negligible owing to low average power and relatively broad pulses (order of 10 fs). The small length of fiber further minimizes the influence of any nonlinear phase shift. In the setup using the GTI, we have estimated round-trip nonlinear phase shift to be ∼0.2 rad. Therefore, although self-phase modulation may contribute to the pulse-shaping mechanism, our observations confirm the dominant role of the SESAM on pulse formation.

The authors would like to thank Liekki Oy for providing the Yb-doped fiber.

References