All-fiber passively mode-locked thulium/holmium laser with two center wavelengths

Rajesh Kadel and Brian R. Washburn*

116 Cardwell Hall, Kansas State University, Department of Physics, Manhattan, Kansas 66506, USA

*Corresponding author: washburn@phys.ksu.edu

Received 18 June 2012; revised 17 August 2012; accepted 17 August 2012;
posted 20 August 2012 (Doc. ID 170797); published 11 September 2012

We have demonstrated a self-starting, passively mode-locked Tm/Ho codoped fiber laser that lases at one of two center wavelengths. An amplified 1.56 μm distributed feedback laser pumps a ring laser cavity which contains 1 m of Tm/Ho codoped silica fiber. Mode locking is obtained via nonlinear polarization rotation using a c-band polarization sensitive isolator with two polarization controllers. The laser is able to pulse separately at either 1.97 or 2.04 μm by altering the intracavity polarization during the initiation of mode locking. The codoped fiber permits pulsing at one of two wavelengths, where the shorter is due to the Tm^{3+} emission and the longer due to the Ho^{3+} emission. The laser produces a stable pulse train at 28.4 MHz with 25 mW average power, and a pulse duration of 966 fs with 9 nm bandwidth. © 2012 Optical Society of America

OCIS codes: 060.2320, 140.3070, 190.4370.

1. Introduction

Continuous and pulsed laser sources in the mid-infrared region (3–10 μm) have long been sought after for many important applications such as medical diagnostics [1], molecular identification [2], or gas monitoring [3]. While continuous mid-IR lasers have been produced by molecular gas lasers or by quantum cascade lasers, high repetition frequency, pulsed mid-IR lasers have been more elusive. Due to the success of using direct frequency comb-based spectroscopy in the visible and near-infrared [4], there is a strong desire to push phase-stabilized frequency combs to the mid-IR, especially to the molecular "fingerprint" region from 2.5 μm to 12 μm. Visible and near-IR combs are generated by phase-stabilized mode-locked lasers that produce femtosecond duration pulses at repetition frequencies in the megahertz. Such combs have been produced using solid-state lasers such as Ti:sapphire or Cr:forsterite; and by rare-earth doped fiber lasers. These lasers have wide bandwidths and thus are able to produce short duration, high peak power pulses. The frequency combs from these lasers can be extended to wavelengths outside their gain bandwidth using fiber nonlinearities.

Unfortunately there are few lasers that can produce mid-IR frequency combs directly. Solid-state lasers produce frequency combs in the visible and near-IR, and these combs can be extended into the mid-IR using difference frequency generation. An alternative method is to use a mode-locked fiber laser-based comb and extend it to the mid-IR using nonlinear effects such as self-phase modulation (SPM). Erbium doped fiber (EDF) lasers are a natural choice since they have been shown to generate combs out to 2.3 μm in highly nonlinear fibers, limited only by the strong IR absorption of fused silica [5]. In principle, chalcogenide or fluoride glass fibers could be used instead since they have better mid-IR transmission.

Thulium or thulium/holmium codoped fiber lasers are a better choice than EDF lasers since they lase near 2 μm and have a broad bandwidth (1.7–2.1 μm) that can support short, high peak power pulses. These pulses could generate a supercontinuum in ZBLAN fiber to extend the comb into the mid-IR. Previously, a Tm-doped passively mode-locked fiber laser with nonlinear polarization rotation and

1559-128X/12/276465-06$15.00/0

spectral filtering as a mode-locking mechanism was reported by Nelson [6], in which the pulse energy was limited to tens of picojoules. The pulse energy can be increased by inserting a dispersion compensator inside the cavity [7]. In both the cases the laser cavity has a free-space section. Wang *et al.* reported an all fiber dispersion management scheme to obtain high pulse energy [8]. Mode locking using carbon nanotubes as a saturable absorber has been demonstrated [9,10]; however, since the carbon nanotubes can be damaged as the energy is increased in the cavity, the output power is limited. Others have demonstrated subpicosecond pulse durations from a Tm fiber laser using an intracavity pulse stretcher [11]. Recently, a phase-stabilized Tm-doped fiber laser-based comb with supercontinuum extending to 3 μm has been demonstrated [12].

Here we have demonstrated a passively mode-locked Tm/Ho doped fiber soliton laser via nonlinear polarization rotation employing a c-band polarization sensitive isolator and output coupler. Mode locking is obtained in a self-starting manner by increasing the pump power without the need of changing the cavity polarization. Furthermore, the laser has the ability to mode lock at one of two different wavelengths by adjusting the position of the polarization controllers and pump power. In order to reduce the pulse duration, we used different fibers that exhibit normal dispersion at 2 μm. The lack of fibers with large normal dispersion at 2 μm makes it difficult to produce sub-500-fs pulses in an all-fiber format with short intracavity fiber lengths in order to maximize the repetition frequency.

2. Mode-Locked Thulium/Holmium Fiber Laser Design

Rare earth doped fiber lasers based on thulium and holmium codopants can be pumped by laser diodes near 1.56 μm and emit light near 2 μm. Lasing in a pure Tm doped fiber occurs between the $^3H_4 - {}^3H_6$ states when pumped at 1.56 μm. The codoping with Ho^{3+} allows for energy transfer from the Tm^{3+} $^3H_4$ to the Ho^{3+} $^5I_7$ state. Lasing on the $^5I_7 - {}^5I_8$ transition of Ho^{3+} [13,14] at wavelengths longer than 2 μm can occur, thus increasing the laser's spectral bandwidth. In general, it is believed that the greater Tm:Ho ratios will ensure that enough Ho^{3+} ions will be sufficiently excited to exceed the transparency level of the laser transition for a given launched power and consequently lead to lower thresholds [15].

The design of our Tm/Ho codoped fiber laser is shown in Fig. 1. A 1.56 μm distributed feedback laser, amplified by an erbium doped fiber amplifier (EDFA) to more than 200 mW, is coupled into the cavity through a 1.55/2 μm wavelength-division-multiplexer (WDM) to pump a length of Coractive TH512 Tm/Ho codoped fiber. According to the manufacturer's specifications, the Tm/Ho codoped fiber had concentrations of 2900 ppm. wt. Tm and <400 ppm. wt. Ho (7.25 : 1 Tm/Ho ratio). The absorption at 1.56 μm was ~12 dB/m. The group velocity dispersion (GVD or β_2) of Corning SMF-28 single-mode fiber

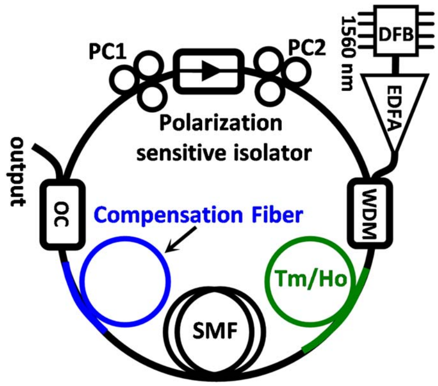


Fig. 1. (Color online) Schematic of the Tm/Ho codoped laser ring cavity. DFB, distributed feedback laser; OC, output coupler; PC, polarization controller; WDM, wavelength division multiplexor; EDFA, erbium doped fiber amplifier.

(SMF) is anomalous (-7.08×10^{-5} fs^2/nm at 1.96 μm). The Tm/Ho fiber GVD was unknown, although we expected it to be anomalous on the order of -10^{-5} fs^2/nm at 1.9 μm based on reported values [6]. A c-band polarization sensitive isolator (AFW technology) with two in-line polarization controllers, PC1 and PC2, are used for passive mode locking. A ~6 m section of SMF, including all the pigtails of the various components, is used to get a sufficient amount of nonlinear phase shift per round trip in the cavity. A c-band 70/30 fiber coupler is used as the output coupler. The laser's spectral output is measured by using a monochrometer and the pulse trains are detected by a 15 MHz bandwidth HgTe photodetector. As discussed below, a compensation fiber was added for intracavity dispersion compensation.

3. Laser Performance

Mode locking was initially obtained with 4 m of Tm/Ho codoped fiber and 7 m of SMF in the cavity. The output spectrum is shown in Fig. 2. The repetition frequency was 18 MHz and the spectral bandwidth was 9 nm full width at half-maximum (FWHM) at 2.04 μm, corresponding to a transform-limited pulse duration of 520 fs. Given that both fibers had anomalous GVD we expected the cavity dispersion times

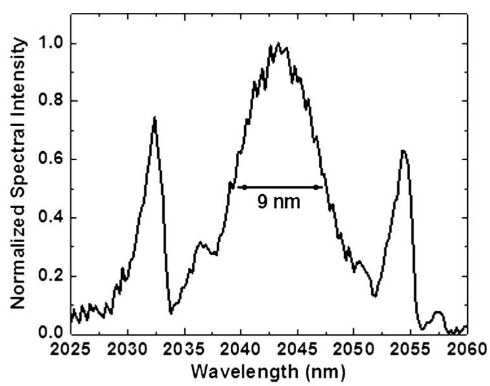


Fig. 2. Mode-locked output spectrum for 4 m of Tm/Ho codoped fiber and 7 m of SMF when pumped at 1.56 μm.

fiber length ($\beta_2 L$), called here the net cavity dispersion, to be negative. The negative net cavity dispersion was verified by the observation of solitonic resonance sidebands known as Kelly sidebands [16]. By measuring the wavelength separation of the Nth order sideband with respect to the center wavelength ($\Delta\lambda_N$) the net cavity dispersion can be computed using [17]

$$\beta_2 L = -\frac{N\lambda_0^2}{\pi c^2}\left[\left(\frac{\Delta\lambda_N}{\lambda_0}\right)^2 + \frac{\ln^2\left(1+\sqrt{2}\right)}{\pi^2}\left(\frac{\lambda_0}{c\Delta\tau}\right)^2\right]^{-1}, \quad (1)$$

where $\Delta\tau$ is the pulse temporal FWHM, λ_0 is the center wavelength, and c is the speed of light.

The spectral bandwidth can be maximized by reducing the net cavity dispersion. This can be achieved either by shortening the lengths of SMF and Tm/Ho fiber in the cavity, or by adding a fiber that has normal dispersion at 2 μm. The latter is typically difficult to do since most silica fibers exhibit anomalous dispersion at 2 μm. However, we expected a highly nonlinear fiber (HNLF) [18] to exhibit normal dispersion at 2 μm and could compensate the anomalous GVD of the SMF and Tm/Ho fiber. HNLF has a similar index profile as a telecomm dispersion compensating fiber [19], which allows for multiple zero GVD points that would exhibit normal dispersion at long wavelengths (Fig. 3). If a larger wavelength separation of the 1st order sideband ($\Delta\lambda_1$) was observed as HNLF was added, Eq. (1) states that the magnitude of the net cavity dispersion would be smaller and thus the HNLF have normal GVD at 1.96 μm. Since the actual GVD of the HNLF was unknown, we relied on a computed GVD value of $\beta_2 + 0.13 \times 10^{-5}$ fs^2/nm at 1.96 μm for a similar HNLF. For this calculated value, the changes in $\Delta\lambda_1$ would be too small (<1 nm) to observe with our spectrometer for meter lengths of added HNLF.

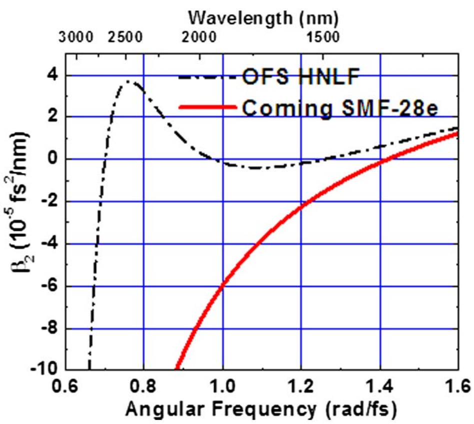


Fig. 3. (Color online) Computed group velocity dispersion of OFS HNLF compared to Corning SMF-28. The HNLF GVD was provided to us from OFS, while the GVD of the SMF was computed using the manufacturer's core size, the Sellmeier coefficients [19], and the weakly guiding approximation.

To test the intracavity dispersion compensation and verify the GVD value above we added HNFL in the laser cavity and measured $\Delta\lambda_1$. No significant outward shifts were observed by adding HNFL, indicating that it has a very small GVD, thus confirming the magnitude of the HNLF's dispersion. The dispersion of the HNLF is too small to compensate the anomalous dispersion while maintaining a repetition frequency of larger than 10 MHz.

Since HNLF could not be used for intracavity dispersion compensation, we minimized the net cavity dispersion by reducing the lengths of Tm/Ho doped fiber and SMF from the cavity while maintaining the mode-locking stability. We found the optimized cavity length to be 7 m with 1 m of Tm/Ho codoped fiber. Initially, mode locking was obtained at pump powers higher than ~200 mW when the two polarization controllers PC1 and PC2 were carefully adjusted. Later, this laser configuration exhibited self-starting operation where mode locking was obtained by only increasing the pump power above threshold without any change in the intracavity polarization. The laser remained mode locked for hours at a time, limited only by the temporal variation of the pump laser polarization. In fact, self starting mode locking has been possible without a change in intracavity polarization over many months of operation. Figure 4 shows the output spectrum of the mode-locked Tm/Ho codoped fiber laser. The output power measured after the output coupler is ~25 mW, with a repetition frequency of 28.4 MHz and spectral bandwidth of 15 nm FWHM. The 28.4 MHz repetition frequency signal was observable using a 15 MHz detector producing a 50 dB signal to noise ratio (300 kHz resolution bandwidth) peak on an electrical spectrum analyzer. The measured repetition frequency was in agreement with the total length of fiber in the laser cavity.

Further optimization would require us to know both the magnitude and sign of the GVD for both the SMF and Tm/Ho fiber. While we are confident in our value for the SMF (which was calculated using the proper Sellmeier coefficients [20], the fiber core size,

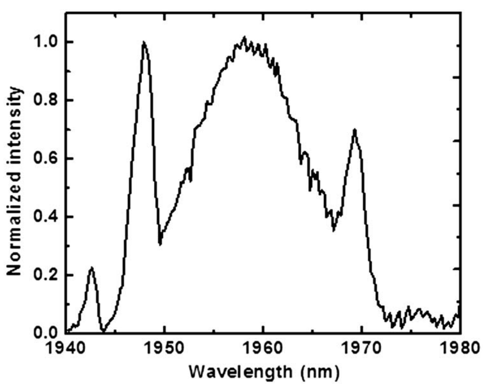


Fig. 4. Mode-locked output spectrum for 1 m of Tm/Ho codoped fiber and 6 m of SMF28 when pumping at 1.56 μm. The spectral width is 15 nm FWHM. Over months of operation the bandwidth reduced to 8 nm.

and the weakly guiding approximation [21]) we only have an order of magnitude approximation from the literature. Equation (1) could be used to compute the GVD of the Tm/Ho codoped fiber, but this requires a measurement of the pulse duration. If we assume transform limited duration for a bandwidth of 15 nm (269 fs) and use the measured sideband spacing, the net cavity dispersion is $\beta_2 L = 1.87 \times 10^{-5}$ fs^2 at 1.96 μm. Given the value of β_2 for SMF and the experimental fiber lengths, we compute a positive value for the Tm/Ho fiber GVD. However, we observe that the sideband wavelength separation increases as we decrease the length of Tm/Ho fiber, indicating that the Tm/Ho fiber has anomalous GVD [as from Eq. (1)]. Therefore, the observed spectra are inconsistent with a transform-limited pulse. Although we cannot measure the Tm/Ho fiber GVD, we can estimate the pulse duration from this measurement. Assuming that the magnitude of the Tm/Ho fiber dispersion is 10^{-5} fs^2/nm, which is on the order of a similar fiber reported in [22], the estimated pulse duration is ~800 fs.

To verify this pulse duration, we later performed an interferometric autocorrelation (IAC) measurement on the laser output [23]. Our setup used a standard Michelson interferometer and detection was accomplished using two-photon detection in an InGaAs detector. We used 1.5/2 μm WDM and Ge filters to ensure no pump 1.56 μm light was incident on the InGaAs detector. The resulting IAC trace is shown in Fig. 5, which exhibits the proper 8 to 1 ratio between peak and background with a FWHM of 1833 fs. Important information about the pulse duration and phase distortion can be discerned from Fig. 5. First, the pulse duration is consistent with the sideband spectral measurements. Here, the analytic expression for the IAC trace for a hyperbolic secant temporal electric field from [23] was used to provide a pulse-to-IAC width ratio of 0.53, which gives a pulse duration of 966 fs. A spectral measurement at the time of the IAC measurement revealed that the bandwidth reduced from 15 nm to 8 nm over the course of six months. The most recent spectrum is shown in the inset of Fig. 5. The cause of the bandwidth reduction is unclear: the bandwidth could not be increased by either changing the position of the optical components or by changing the intracavity polarization. We believe that the insertion loss of the polarization sensitive isolator may have increased over the six months, caused possibly by inadvertently passing more than the maximum recommended power (300 mW) through the isolator during the initial mode-locking attempts. Increasing the insertion loss will create a larger cavity loss, so the gain will be saturated less when lasing occurs. Due to the wavelength-dependent absorption and emission cross section, this will change the center wavelength. A reduction of intracavity power will also reduce the total nonlinear phase shift and thus the spectral width.

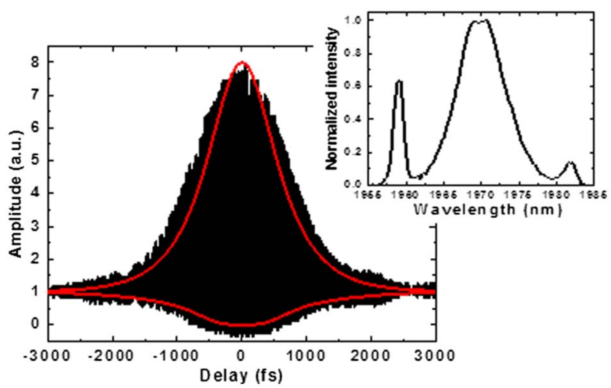


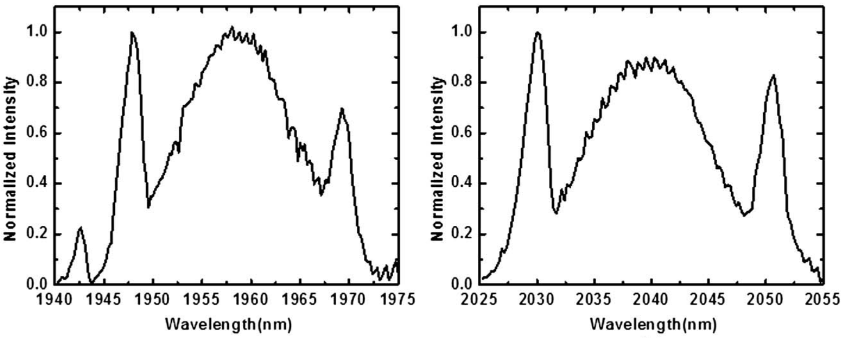
Fig. 5. (Color online) Interferometric autocorrelation trace of the laser output. The autocorrelation FWHM was 1833 fs, corresponding to a pulse duration of 966 fs. The computed IAC envelope for a 966 fs pulse that exhibits self-phase modulation is plotted for comparison. The inset is the corresponding spectrum of 8 nm FWHM at the time of the IAC measurement.

Information about the pulse's phase distortion can be deduced from the IAC trace as well. The phase distortion is primarily due to SPM and not GVD since the IAC measurement exhibits fringes across the entire trace [23]. SPM preserves the pulse coherence and thus fringes can be seen across the entire IAC trace, which is not the case for a pulse that exhibits only second order phase distortion. The computed IAC envelope for a pulse of duration 966 fs that exhibits only SPM is plotted for comparison.

4. Mode Locking at Different Center Wavelengths

The laser is able to mode lock at one of two center wavelengths by carefully adjusting the intracavity polarization during the process of mode locking. The output pulse spectra at two different center wavelengths ~80 nm apart are shown in Fig. 6. The left spectrum is centered at 1.96 μm with a FWHM bandwidth of ~15 nm and the output power measured is ~25 mW. Mode locking can be stopped by external perturbation, decreasing the pump power, or changing the position of polarization controllers. Once the mode locking has been terminated, it can be initiated again with the same pump power but at a different position of the polarization controller and at a different center wavelength. The right spectrum shows the mode-locked spectrum at center wavelength 2.04 μm with a bandwidth of 13 nm and the output power is almost the same.

The ability to lase on one of two center wavelengths is a result of the Tm/Ho codoping. For Tm/Ho fiber lengths of ~1 m, it has been observed that the ASE exhibits a peak near 2 μm but a shoulder near 1.9 μm [13]. The emission at 1.97 μm is due to the Tm^{3+} emission while the 2.04 μm is due to Ho^{3+}. In another study [24], the fluorescence from a 6:1 ratio Tm/Ho fiber was measured as a function of fiber length. Fiber lengths smaller than 0.5 m exhibited more fluorescence at ~1.97 μm compared ~2.04 μm, while a fiber of ~1 m exhibited similar levels of fluorescence at these two wavelengths. Longer fibers have reduced emission at the shorter



(a) (b)

Fig. 6. Mode-locked spectrum for 1 m of Tm/Ho codoped fiber when pump power is ~300 mW with center wavelengths at (a) 1.96 μm and (b) 2.04 μm. Each spectrum was obtained under separate mode-locking conditions.

wavelength due to the energy transfer from Tm^{3+} to Ho^{3+}, and due to reabsorption of the Tm^{3+} emission [24]. To optimize the ability to mode lock at these center wavelengths, the fiber length must be chosen to permit some energy transfer but not at the cost of depleting the Tm^{3+} emission.

5. Conclusion

We have demonstrated a mode-locked Tm/Ho codoped fiber ring laser that can lase on one of two center wavelengths. The final laser configuration, with 1 m of Tm/Ho fiber and 6 m of SMF, self started by increasing the pump power above the mode-locking threshold without any change of the cavity polarization. The sideband wavelength separation and IAC trace a pulse duration of 966 fs for the pulse centered at 1970 nm with 8 nm bandwidth. This pulse exhibited a phase distortion associated with SPM as indicated by the interference fringes across the entire IAC trace.

The lack of normal group velocity dispersion fiber at 2 μm prevented us from using intracavity dispersion compensation to produce short output pulses at a high repetition rate in an all-fiber format. However, the SPM-like nonlinear phase distortion indicated by the IAC measurement shows that compression can be accomplished using a medium that exhibits only anomalous GVD without any nonlinear effect. Shorter pulses potentially could be obtained by adding a grating or prism compressor, or by using a hollow core photonic crystal fiber that exhibits anomalous GVD at the laser's center wavelength.

This research was supported jointly by U.S. Air Force Office of Scientific Research (USAFOSR) contract No. FA9950-10-1-00515. The authors are grateful to Jeffrey Nicholson for the dispersion data of highly nonlinear fiber, Andrew Jones for assistance with the high power EDFA, and Kristan Corwin for helpful discussions.

References

1. P. Mazzone, "Analysis of volatile organic compounds in the exhaled breath for the diagnosis of lung cancer," J. Thorac. Oncol. **3**, 774–780 (2008).
2. K. Namjou, C. B. Roller, T. Reich, J. Jeffers, G. McMillen, P. McCann, and M. Camp, "Determination of exhaled nitric oxide distributions in a diverse sample population using tunable diode laser absorption spectroscopy," Appl. Phys. B **85**, 427 (2006).
3. F. Tittel, D. Richter, and A. Fried, "Mid-infrared laser applications in spectroscopy," in *Solid-State Mid-Infrared Laser Sources* (Springer, 2003), pp. 445–510.
4. M. J. Thorpe and J. Ye, "Cavity-enhanced direct comb spectroscopy," Appl. Phys. B **91**, 397–414 (2008).
5. T. Izawa, N. Shibata, and A. Takeda, "Optical attenuation in pure and doped fused silica in the IR wavelength region," Appl. Phys. Lett. **31**, 33 (1977).
6. L. E. Nelson, E. P. Ippen, and H. A. Haus, "Broadly tunable sub-500 fs pulses from an additive-pulse mode-locked thulium-doped fiber ring laser," Appl. Phys. Lett. **67**, 19–21 (1995).
7. M. Engelbrecht, F. Haxsen, A. Ruehl, D. Wandt, and D. Kracht, "Ultrafast thulium-doped fiber-oscillator with pulse energy of 4.3 nJ," Opt. Lett. **33**, 690–692 (2008).
8. Q. Wang, T. Chen, and K. Chen, "Mode-locked ultrafast thulium fiber laser with all fiber dispersion management," in *Proceedings of the Conference on Lasers and Electro-optics* (Optical Society of America, 2010), paper CFK7.
9. M. A. Solodyankin, E. D. Obraztsova, A. S. Lobach, A. I. Chernov, A. V. Tausenev, V. I. Konov, and E. M. Dianov, "Mode-locked 1.93 μm thulium fiber laser with a carbon nanotube absorber," Opt. Lett. **33**, 1336–1338 (2008).
10. K. Kieu and F. W. Wise, "Soliton thulium-doped fiber laser with carbon nanotube saturable absorber," IEEE Photon. Technol. Lett. **21**, 128–130 (2009).
11. F. Haxen, D. Wandt, U. Morgner, J. Neumann, and D. Kracht, "Pulse characteristics of a passively mode-locked thulium fiber laser with positive and negative cavity dispersion," Opt. Express **18**, 18981–18988 (2010).
12. C. R. Philips, J. Jiang, C. Langrock, M. M. Fejer, and M. E. Fermann, "Self-referenced frequency comb from a Tm-fiber via PPLN waveguide supercontinuum generation," in *Proceedings of the Conference on Lasers and Electro-optics* (Optical Society of America, 2011), paper PDPA5.
13. K. Oh, T. F. Morse, A. Kilian, L. Reinhart, and P. M. Weber, "Continuous-wave oscillation on thulium-sensitized holmium-doped silica fiber laser," Opt. Lett. **19**, 278–280 (1994).
14. C. Ghisler, W. Luthy, H. P. Weber, J. Morel, A. Woodtli, T. Dändliker, V. Neuman, H. Berthou, and G. Kotortsios, "A Tm^{3+} sensitized Ho^{3+} silica fiber laser at 2.04 μm pumped at 809 nm," Opt. Commun. **109**, 279–281 (1994).
15. S. D. Jackson and T. A. King, "CW operation of a 1.064 μm pumped Tm-Ho-doped silica fiber laser," IEEE J. Quantum Electron. **34**, 1578–1587 (1998).
16. S. M. J. Kelley, "Characteristic sideband instability of periodically amplified average soliton," Electron. Lett. **28**, 806–808 (1992).
17. M. L. Dennis and I. N. Duling III, "Experimental study of sideband generation in Femtosecond fiber laser," IEEE J. Quantum Electron. **30**, 1469–1477 (1994).
18. J. W. Nicholson, M. F. Yan, P. Wisk, J. Fleming, F. DiMarcello, E. Monberg, A. Yablon, C. Jørgensen, and T. Veng, "All-fiber, octave-spanning supercontinuum," Opt. Lett. **28**, 643–645 (2003).

19. L. Grüner-Nielsen, M. Wandel, P. Kristensen, C. Jørgensen, L. V. Jørgensen, B. Edvold, B. Pálsdóttir, and D. Jakobsen, "Dispersion-compensating fibers," J. Lightwave Technol. **23**, 3566–3579 (2005).
20. J. A. Buck, *Fundamentals of Optical Fibers*, 2nd ed. (Wiley, 2004).
21. D. Gloge, "Weakly guiding fibers," Appl. Opt. **10**, 2252–2258 (1971).
22. S. Kivistö, T. Hakulinen, M. Guina, and O. G. Okhotnikv, "Tunable Raman soliton source using mode-locked Tm-Ho fiber laser," IEEE Photon. Technol. Lett. **19**, 934–936 (2007).
23. J. C. M. Diels, J. J. Fontaine, I. C. McMichael, and F. Simoni, "Control and measurement of ultrashort pulse shapes (in amplitude and phase) with femtosecond accuracy," Appl. Opt. **24**, 1270–1282 (1985).
24. S. Y. Chen, T. L. Yeo, J. Leighton, T. Sun, K. T. V. Grattan, R. Lade, B. D. Powell, G. Foster-Turner, and M. Osborne, "Tm:Ho co-doped single mode optical fiber laser pumped by a 1600 nm Er fiber laser," Opt. Commun. **281**, 2567–2571 (2008).