All-fiber wavelength-swept laser near 2 μm

Jihong Geng,[1,*] Qing Wang,[1] Jiafu Wang,[1] Shibin Jiang,[1] and Kevin Hsu[2]

[1]AdValue Photonics, 3708 East Columbia Street, Suite 100, Tucson, Arizona 85714, USA

[2]Micron Optics, 1852 Century Place, Atlanta, Georgia 30345, USA

*Corresponding author: jgeng@advaluephotonics.com

Received August 1, 2011; revised August 29, 2011; accepted August 31, 2011;
posted September 2, 2011 (Doc. ID 152171); published September 20, 2011

We report, for the first time to our knowledge, an all-fiber wavelength-swept Tm-doped laser based on a fiber Fabry–Perot tunable filter in the 2 μm spectral region. The laser wavelength can be continuously tuned over 200 nm from 1840 to 2040 nm in a short period of time. The demonstrated tuning speed was 12.5 μm/s with a tuning efficiency of 17.5 nm/V. The spectral linewidth of the laser was measured to be approximately 300 MHz or 0.01 cm^{-1}. This kind of laser can find potential applications in both high-resolution laser spectroscopy and tunable mid-IR generation via nonlinear frequency conversion.

OCIS codes: 060.2320, 140.3510, 140.3570, 140.3600.

Laser sources near 2 μm based on Tm^{3+} and Ho^{3+} ions have attracted intense interest in recent decades for their potential applications. For example, atmospheric lidar sensing application requires compact highly reliable laser sources near 2 μm for airborne and spaceborne atmosphere measurements [1,2] by utilizing abundant characteristic absorption lines of atmospheric H_2O and CO_2 in this spectral region. Another emerging application for 2 μm lasers is to use them as a pump source for longer wavelength IR generation via nonlinear frequency conversion, such as with an optical parametric oscillator (OPO) [3]. Obviously, these applications can greatly benefit if the wavelength of 2 μm lasers can be widely tuned.

Broad wavelength tunability of both a Tm-doped crystalline laser [4] and Tm-doped fiber laser [5] has been reported for two decades, with average output power at the several or even tens of watts level demonstrated recently [6,7]. However, these previous demonstrations use fragile free-space laser cavity designs, even in those Tm-doped fiber lasers. In this Letter, we report an all-fiber wavelength-tunable Tm-doped fiber laser, whose wavelength can be rapidly swept over a wide spectral range by using a fiber Fabry–Perot tunable filter (FFP-TF). This kind of fiber laser has been demonstrated in the 1 and 1.55 μm wavelength regions [8,9], and here we report the first demonstration (to our knowledge) in the 2 μm wavelength region.

The critical wavelength-tuning operation is accomplished by the FFP-TF designed for the 2 μm region using Micron Optics' patented technology, as illustrated in Fig. 1. As a seminal advancement from traditional bulk-optic Fabry–Perot filters, the FFP-TF technology is an all-fiber device having a concave cavity formed by two mirrors deposited directly onto fiber ends. A thin air gap within the cavity is used for wavelength tuning and control by a piezoelectric transducer (PZT) with positioning resolution of atomic dimensions. The key to the stable, high performance characteristics of this device is the incorporation of intrinsic beam shaping mechanism that provides intracavity waveguiding, elimination of extraneous cavity modes, and ease of mirror alignment required for high-finesse and low-loss operation.

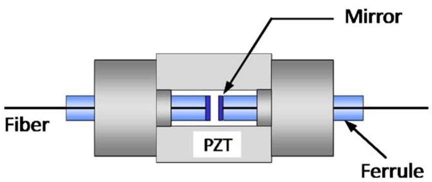

Fig. 1. (Color online) Illustration of the FFP-TF structure.

The FFP-TF used in this experiment has a free spectral range (FSR) of ~300 nm, an insertion loss of ~1 dB, and a finesse of ~2300, as characterized by a single-frequency laser [10]. The measured FSR and finesse reveal that the mirror reflectivity of the FFP-TF is about 99.863% with an air gap thickness of 6.3 μm. In Fig. 2, the yellow (upper) trace is the input spectrum of an in-house broadband mid-IR supercontinuum fiber source, while the pink (lower) trace shows a typical narrow-line transmission spectrum of the filter, with an FWHM bandwidth of 0.13 nm over a wide spectral range, e.g., from 1850 to 2150 nm. By applying a sawtooth tuning voltage to the filter, its transmission wavelength can be rapidly swept, as shown in the green (middle) trace in Fig. 2 [note the high edges of the swept spectrum are due to the integration effect of the optical spectrum analyzer (OSA)].

The Tm-doped all-fiber wavelength-swept laser incorporating the FFP-TF is illustrated in Fig. 3. A cw single-mode fiber source at 1.56 μm was used to core pump a piece of single-mode Tm-doped fiber via a fiber

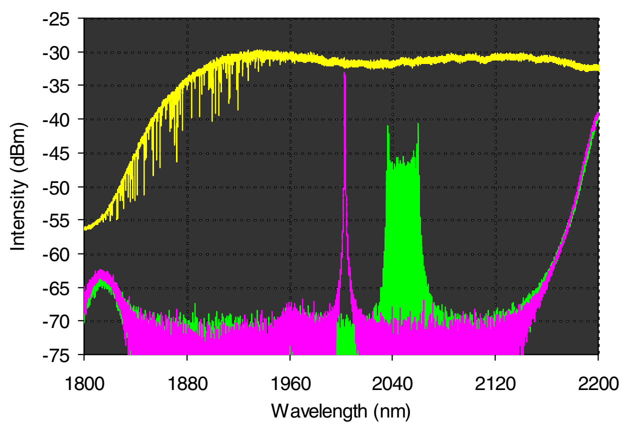

Fig. 2. (Color online) The FFP-TF is characterized by a mid-IR supercontinuum fiber source; yellow (upper) trace, supercontinuum spectrum; pink (lower) trace, transmission spectrum with a constant voltage; and green (middle) trace, transmission spectrum with a sawtooth voltage.

0146-9592/11/193771-03$15.00/0

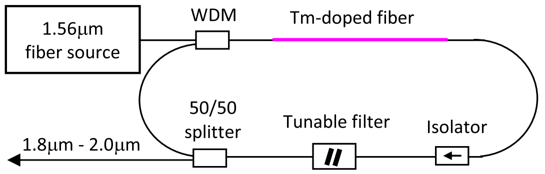

Fig. 3. (Color online) Schematic diagram of an all-fiber wavelength-swept laser near 2 μm.

wavelength-division multiplexer (WDM) for the wavelength at 1.5 μm/2.0 μm. The length of the Tm-doped fiber was approximately 50 cm. All of the intracavity components, including an isolator, the tunable filter, and a 50/50 splitter, were fusion spliced together to form an all-fiber laser ring cavity with a cavity length of about 8 m.

The laser wavelength was determined by the transmission wavelength of the tunable filter, which in turn was piezoelectrically controlled by the voltage that was applied to the filter. Figure 4 shows typical laser spectra when constant voltages (upper graph) or a swept voltage (lower graph) was applied to the filter. The graphs were recorded with a Yokagawa OSA. The lower graph was obtained when the OSA was scanning many times in a maximum-hold mode. No synchronization was applied between the laser wavelength scans and the OSA scans. The laser wavelength can be tuned over 200 nm from 1840 to 2040 nm.

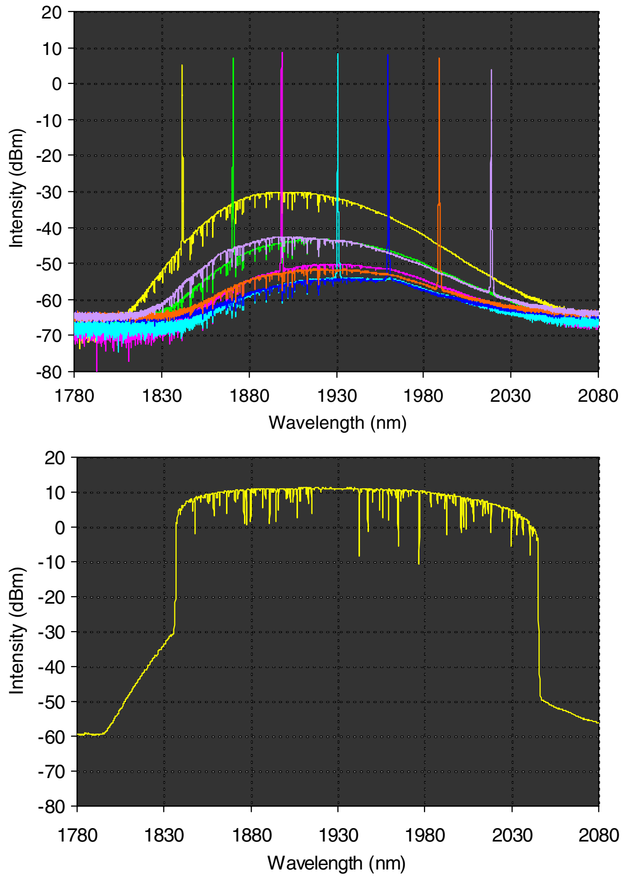

Fig. 4. (Color online) Typical laser spectra when constant voltages (upper) and a swept voltage (lower) were applied to the tunable filter. In the lower graph, some wavelengths were not caught by the OSA during the scans due to no synchronization.

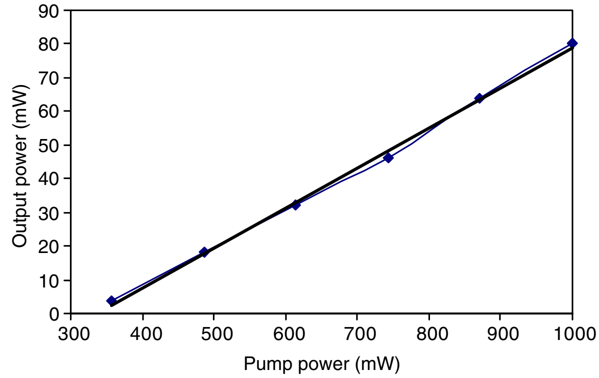

Fig. 5. (Color online) Output power of the laser at 1930 nm as a function of the pump power.

When pumping at 1 W with the 1.56 μm laser, the output power was ~80 mW at the center of the tuning range (1900–1960 nm), and gradually decreased when approaching both ends of the tuning range. Figure 5 shows output power of the laser operating at 1930 nm as a function of launched pumped power. The corresponding slope efficiency was measured to be 12% at the wavelength. No effort was made to optimize the laser efficiency in this experiment. We believe that the losses of the intracavity components, including ~0.5 dB loss for WDM, ~1 dB for the isolator, ~1 dB for the filter, and ~0.5 dB extra loss for the 50/50 splitter should be partly responsible for the relatively low slope efficiency.

When a sawtooth voltage is applied to the filter, the laser wavelength can be swept rapidly. Figure 6 shows the temporal profile of the laser intensity during a laser sweep. It can be seen that the laser wavelength was swept over 200 nm in just about 16 ms, at a speed of 12.5 μm/s. The voltage required to achieve 200 nm wavelength tuning is ~11.4 V, corresponding to a tuning efficiency of 17.5 nm/V. Note that the sweep speed is presently limited by the filter driver. The maximum sweep rate will depend on a combination of factors, including laser cavity net gain, round-trip time, and filter tuning speed limitation.

The dynamic operation of the laser, i.e., fast wavelength sweeping, has a high repeatability and reproducibility. However, it should be noted that in a static operation mode (with a constant voltage), the laser

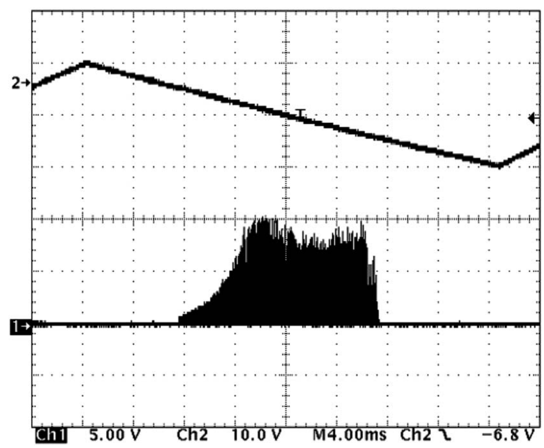

Fig. 6. Temporal profile of the laser intensity when the laser wavelength was swept over 200 nm in 16 ms.

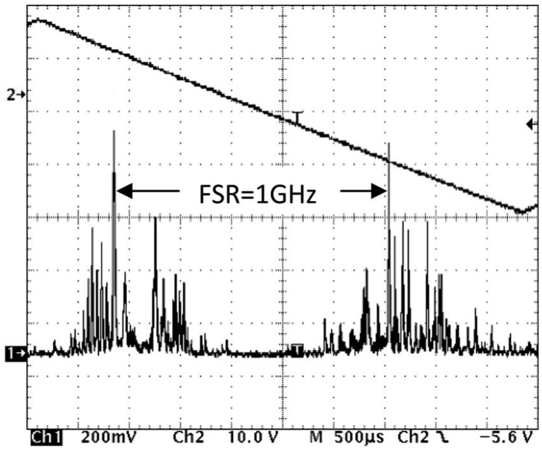

Fig. 7. Laser spectral linewidth is measured by using a high-resolution scanning FP interferometer with an FSR = 1 GHz and a finesse of ∼270.

wavelength can drift at a rate varying from <0.1 nm/min to >1 nm/min, which is heavily dependent on the operation history of the PZT actuator, as expected. In general, the drift is high initially when the laser is switched from sweep mode to static mode, and then it gradually slows down over time.

The slow drift of the laser wavelength in a static mode could be an issue for some applications. The wavelength drift is the result of a nonnegligible temperature sensitivity of the tunable filter (about 1% of FSR per Kelvin, i.e., ∼3 nm/°C for the unit in this experiment). But for other applications where stable laser operation at a specific wavelength is needed, the capability of fast wavelength tuning of the laser offers a possibility to lock the laser operation wavelength to an external wavelength reference, just as demonstrated in a similar Er-doped tunable fiber laser [8].

Spectral linewidth of the laser was measured by using a high-resolution scanning fiber Fabry–Perot interferometer (Micron Optics) with an FSR of 1 GHz and a finesse of ∼270. Figure 7 shows a typical scanning spectrum of the laser over one FSR. The measured spectral linewidth was about ∼300 MHz, or 0.01 cm^{-1}. The narrow-linewidth tunable laser can be used for high-resolution spectroscopic measurements.

It is easy to switch the laser operation from cw mode to pulsed mode, simply by changing the operation mode of the 1.56 μm pump laser from cw mode to pulsed mode. The in-band pump configuration in a Tm-doped fiber laser enables an easy way to generate gain-switched pulses near 2 μm, as previously demonstrated [11]. A pulsed wavelength-tunable 2 μm fiber source will be extremely useful for tunable mid-IR generation via nonlinear frequency conversion, such as OPO [3].

In summary, an all-fiber wavelength-swept Tm-doped fiber laser has been demonstrated by using an FFP-TF. The laser wavelength can be rapidly tuned over 200 nm from 1840 to 2040 nm at a speed as high as 12.5 μm/s, and tuning efficiency of ∼17.5 nm/V. The spectral linewidth of the tunable laser is ∼300 MHz or 0.01 cm^{-1}, which allows for performing high-resolution laser spectroscopy. This type of laser can also be used in the application for longer-wavelength-tunable IR generation via nonlinear frequency conversion.

References

1. S. W. Henderson, P. J. M. Suni, C. P. Hale, S. M. Hannon, J. R. Magee, D. L. Bruns, and E. H. Yuen, IEEE Trans. Geosci. Remote Sensing **31**, 4 (1993).
2. J. Yu, B. C. Trieu, E. A. Modlin, U. N. Singh, M. J. Kavaya, S. Chen, Y. Bai, P. J. Petzar, and M. Petros, Opt. Lett. **31**, 462 (2006).
3. S. Chandra, M. E. Wager, B. Clayton, A. G. Geiser, T. H. Allik, J. L. Ahl, C. R. Miller, P. A. Budni, P. A. Ketteridge, K. G. Lanier, E. P. Chicklis, J. A. Hutchinson, and W. W. Hovis, Proc. SPIE **4036**, 200 (2000).
4. R. C. Stoneman and L. Esterowitz, Opt. Lett. **15**, 486 (1990).
5. D. C. Hanna, R. M. Percival, R. G. Smart, and A. C. Tropper, Opt. Commun. **75**, 283 (1990).
6. J. Nilsson, W. A. Clarkson, R. Selvas, J. K. Sahu, P. W. Turner, S. U. Alam, and A. B. Grundinin, Opt. Fiber Technol. **10**, 5 (2004).
7. F. Wang, D. Y. Shen, D. Y. Fan, and Q. S. Lu, Laser Phys. Lett. **7**, 450 (2010).
8. T. Haber, K. Hsu, C. M. Miller, and Y. Bao, IEEE Photon. Technol. Lett. **12**, 1456 (2000).
9. F. D. Nielsen, L. Thrane, J. Black, K. Hsu, A. Bjarklev, P. E. Andersen, Proc. SPIE **5861**, 58610H (2005).
10. J. Geng, Q. Wang, T. Luo, S. Jiang, and F. Amzajerdian, Opt. Lett. **34**, 3493 (2009).
11. M. Jiang and P. Tayebati, Opt. Lett. **32**, 1797 (2007).