

Single-longitudinal-mode tunable WDM-channel-selectable fiber laser

Nathaniel J. C. Libatique, Li Wang, and Ravi K. Jain

Dept. of Electrical Engineering and Computer Engineering, University of New Mexico, Albuquerque, NM, USA
natl@chtm.unm.edu, jain@chtm.unm.edu

Abstract: We report operation of a single-longitudinal-mode WDM-channel-selectable fiber laser. The use of a tunable fiber Bragg grating and a linewidth narrowing saturable absorption filter in conjunction with an intracavity etalon enabled single-frequency emission and discretely tunable WDM channel operation without the need for external wavelength locking modules. Side mode suppression ratios (SMSRs) > 50 dB have been demonstrated with ~ 3 dBm individual channel output powers for 8 channel ($\Delta f = 50$ GHz) operation of this WDM source.

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References and Links

1. T. Haber, K. Hsu, C. Miller, and Y. Bao, "Tunable EDF Laser precisely locked to the 50 GHz ITU frequency grid," in *Europ. Conf. on Opt. Commun.*, (Nice, France, 1999), Paper Mo B2.4.
2. A. Bellemare, J.-F. Lemieux, M. Tetu, and S. Larochelle, "Er-doped fiber ring lasers step-tunable to exact multiples of 100 GHz (ITU-Grid) using periodic filters," in *Europ. Conf. on Opt. Commun.*, (Madrid, Spain, 1998), 153-154.
3. N. J. C. Libatique and R. K. Jain, "A Broadly Tunable Wavelength-Selectable WDM Source Using a Fiber Sagnac Loop Filter," *IEEE Photon. Technol. Lett.* **13**, 1283-1285 (2001).
4. M. Ibsen, S. Y. Set, G. S. Goh, and K. Kikuchi, "Broad-band continuously tunable all-fiber DFB lasers," *IEEE Photon. Technol. Lett.* **14**, 21-23 (2002).
5. D. M. Adams, C. Gamache, R. Finlay, M. Cyr, K. M. Burt, J. Evans, E. Jamroz, S. Wallace, I. Woods, L. Doran, P. Ayliffe, D. Goodchild, and C. Rogers, "Module packaged tunable laser and wavelength locker delivering 40 mW of fibre-coupled power on 34 channels," *Electron. Lett.* **37**, 691-693 (2001).
6. M. Mesh and Y. Weiss, "Device and method for monitoring and controlling laser wavelength," Patent 6,233,262, ECI Telecom Ltd., May 15, 2001.
7. G. H. Cross and E. E. Strachan, "Diode laser wavelength tracking using an integrated dual slab waveguide interferometer," *IEEE Photon. Technol. Lett.* **14**, 950-952 (2002).
8. M. A. Putnam, R.N. Brucato, M. A. Davis, D. G. Bellemore, and W. A. Helm, "Tunable optical structure featuring feedback control," *Patent # 6,310,990*, Cidra Corporation, October 30, 2001.
9. M. Horowitz, R. Daisy, B. Fischer, and J. Zyskind, "Narrow-linewidth, singlemode erbium-doped fibre laser with intracavity wave mixing in saturable absorber," *Electron. Lett.* **30**, 648-649 (1994).
10. Y. W. Song, S. A. Havstad, D. Starodubov, Y. Xie, A. E. Willner, and J. Feinberg, "40-nm-wide tunable fiber ring laser with single-mode operation using a highly stretchable FBG," *IEEE Photon. Technol. Lett.*, **13**, 1167-1169 (2001).
11. G. A. Ball and W. W. Morey, "Compression-tuned single-frequency Bragg grating fiber laser," *Opt. Lett.*, **19**, pp. 1979-1981 (1994).

Discretely tunable channel-selectable fiber laser sources [1-3] have been demonstrated as attractive alternatives to conventional external cavity and monolithic semiconductor laser sources as high performance tunable WDM (wavelength-division-multiplexed) sources. Unfortunately most previous channel-selectable WDM fiber lasers [2,3] have been characterized by multi-longitudinal mode outputs, a feature that has limited their usability for WDM applications. Fiber lasers based on DFB (distributed feedback) structures [4] have been demonstrated to be singlemoded and tunable, however, because of the nature of the DFB

feedback mechanism, these lasers are not amenable to the insertion of passive etalon-type grid filters that are “automatically” matched to the ITU grid; as such, incorporating channel selectability in fiber DFB lasers will involve more complex emission wavelength or fiber grating displacement monitoring and feedback mechanisms (based on the use of external wavelength-locking sub-systems [5-7] or capacitive displacement sensors [8]).

In this Letter, we report *operation of a single longitudinal mode discretely tunable channel-selectable ($\Delta f = 50$ GHz) WDM laser*. This is achieved by taking advantage of line narrowing intracavity filters based on saturable absorber fibers [9-10] along with an intracavity glass etalon for channel pinning to the ITU grid [2]. Such narrow linewidth discretely tunable lasers have high potential for low noise WDM systems applications. In addition, the laser is constructed from readily available & off-the-shelf parts and components and as such are potentially manufacturable at relatively low set-up costs.

The fiber laser layout is based on a “hybrid” sigma-shaped fiber cavity, similar to that of Ref. [10], obtained by coupling a ring cavity to a linear standing wave arm via a 3-port circulator, as depicted schematically in Fig. 1. A glass etalon (2 mm thick, 50 GHz free spectral range, 10 dB transmission peak-to-valley ratios) was inserted in the ring cavity to act

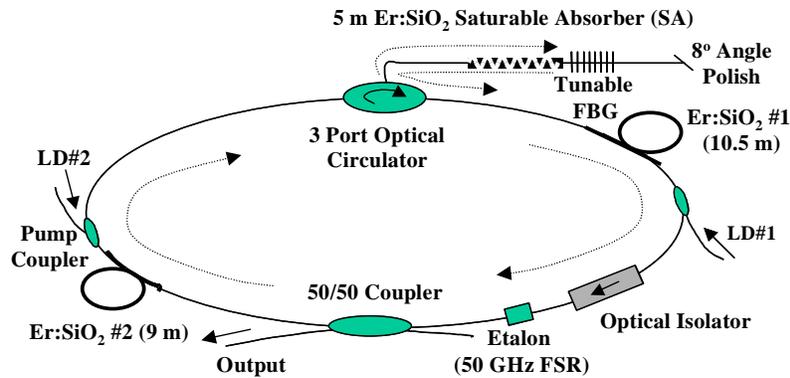


Fig. 1. Schematic of discretely tunable WDM laser source

as a frequency-periodic transmission filter referenced to the ITU-WDM 50 GHz grid. Specific channel tunability and mode selection were achieved by using a tunable fiber Bragg grating (3 dB linewidth < 0.05 nm) and a 5 m long Er:SiO₂ saturable absorber (SA) fiber in the linear standing wave arm. A key feature of this linear arm is that the counterpropagating waves set up a spatial absorption modulation consisting of saturated (non-absorbing) and unsaturated (absorbing, lossy) regions along the entire length of the saturable absorber fiber, which can cause very large losses at neighboring longitudinal modes while allowing high transmission at the favored longitudinal mode to effectively narrow the linewidth of the FBG relatively efficiently. In order to have sufficient *control of the intracavity power* for optimized operation of this saturable absorber line narrowing filter, we placed two sections of 980 nm LD (laser diode)-pumped Er:SiO₂ amplifiers in the ring cavity and adjusted the relative pump levels of these two sections appropriately as discussed below, to obtain single mode output operation while obtaining significant output power. Output coupling of laser power was achieved with the use of a 50/50 fused fiber coupler in the ring.

Stepwise tuning of this wavelength-selectable WDM fiber laser is easily achieved by tuning the FBG, with output channel wavelengths determined by the Fabry-Perot etalon transmission peak spacing ($\Delta f = 50$ GHz). *Nevertheless, achievement of single-mode operation of the laser source, at the target output power levels at these selected WDM channels, requires appropriate optimization of the saturable absorption.* This was achieved by an appropriate choice of the length of the saturable absorber fiber and appropriate control of the pump powers for the two intracavity amplifiers (EDFAs). In our design we targeted an

output power of ~ 3 dBm. The length of the Er:SiO₂ saturable absorber fiber was then chosen such that the absorption saturation power P_{sat} of the fiber was at least 3 dB lower than the 3 dBm target output power ($P_{\text{sat}} \leq 0$ dBm). *Of the 3 fiber lengths available (Thorlabs EDF555: 1.5 m, 3.5 m, and 5 m lengths) that satisfied this condition, we chose the 5 m length, which had the highest saturated-to-unsaturated absorption loss differential of ~ 15 dB (vs. 8.5 dB & 4 dB for the 3.5 m & 1.5 m fibers respectively), as determined by absorption measurements at 1550 nm. Longer lengths of fiber can be used to increase this absorption differential (~ 30 dB estimated for ~ 10 m long fibers), however larger intracavity powers will be required to realize this. Further optimization of the saturable absorption was done by studying the output spectrum as a function of pump power with scanning Fabry-Perot interferometry (FPI) and self-heterodyne RF spectroscopy as described below.*

Figure 2a shows a scanning FPI measurement of the laser output *with no saturable absorber present in the cavity*. For this measurement, the power of the first 980 nm pump laser diode (LD#1) P_{p1} was set at 180 mW, and the power of the second laser diode (LD#2) P_{p2} was set at 200 mW. The result, as seen in Fig 2a, shows spectrally unstable laser operation at multiple modes. Figure 2b shows an FPI scan when an unpumped of Er:SiO₂ saturable

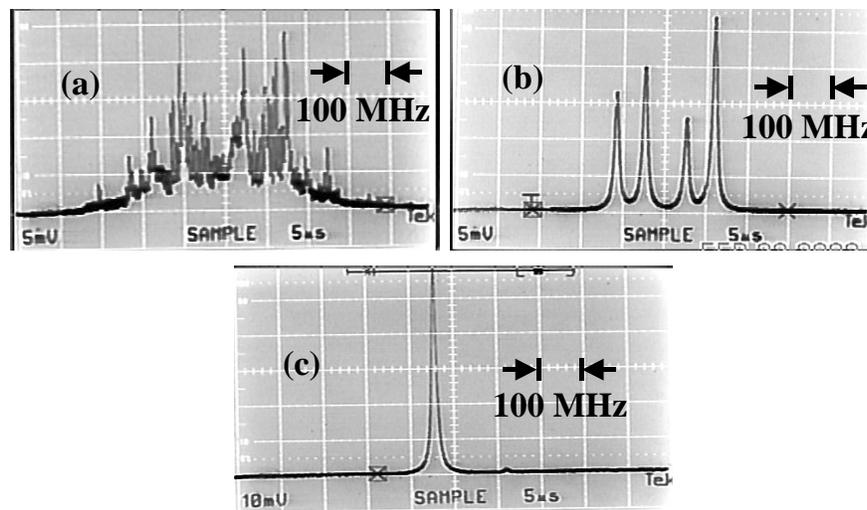


Fig. 2. Laser output, as a function of LD#2 pump power P_{p2} , measured via Fabry-Perot interferometry with 20 MHz resolution (a) no saturable absorber (SA), $P_{p2} = 200$ mW, highly multimode (b) with 5 m saturable absorber, $P_{p2} = 200$ mW (c) with 5 m saturable absorber, $P_{p2} = 35$ mW, stable singlemode output

absorber fiber (of 5 m length) was inserted in the cavity, immediately showing a marked reduction in the modal noise. However the output was still spectrally unstable at high P_{p2} (> 50 mW) pump power levels. Finally, stable singlemode operation was achieved (Fig. 2c) by reducing P_{p2} , the pump power of LD#2, to 35 mW. Note that although the scan covers a range of only 1 GHz (50 μ s in the scope display) of the scanning Fabry-Perot's 20 GHz FSR (free spectral range), *a full scan over the whole FSR (not shown in Fig. 2c) confirmed single mode operation (i.e. no other longitudinal mode was observed).*

Since the transmission linewidth (20 MHz) of the FPI was too large to resolve the laser mode spacing (~ 3 MHz), a self-heterodyne measurement (SHM) was used to confirm single frequency emission. Fig. 3a shows the self-heterodyne data when the saturable absorber was not spliced to the FBG and with P_{p2} set to 200 mW. As expected (from the data in Fig. 2a) the emission in this case was multimode and extended over a broad spectral range (1 MHz - 400

MHz). With the saturable absorber connected to the FBG and for the same pump power ($P_{p2} = 200$ mW), we observed (Fig. 3b, 1 MHz – 50 MHz range) significant narrowing (from ~ 400 MHz to 15 MHz) of the spectral range of the multimode emission. By comparing this data to that of Fig. 2b, it is clear that under these conditions, the laser has a tendency to mode hop from one longitudinal mode to another. *As seen in Fig. 3c, single longitudinal mode*

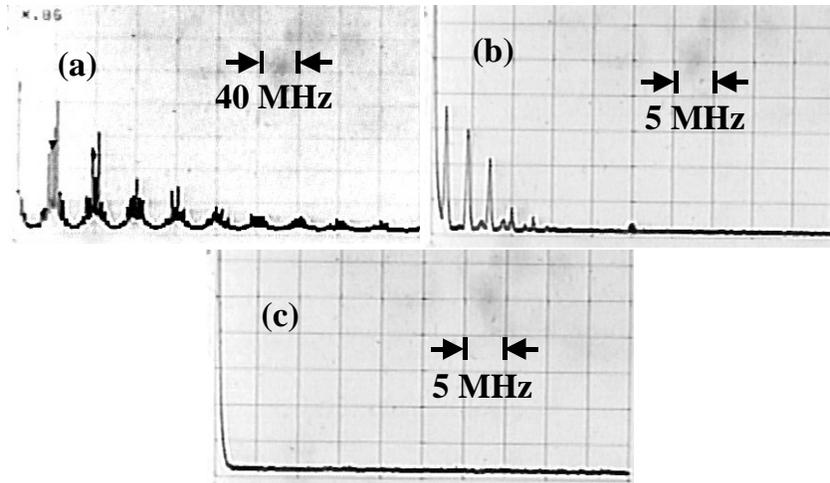


Fig. 3. Laser output, as a function of LD#2 pump power P_{p2} , measured via self-heterodyne measurements with 300 kHz resolution (a) no saturable absorber (SA), $P_{p2} = 200$ mW, highly multimode (b) with 5 m saturable absorber, $P_{p2} = 200$ mW, RF beating of 6 modes (c) with 5 m saturable absorber, $P_{p2} = 35$ mW, stable singlemode output

operation was achieved for P_{p2} set to 35 mW (as seen previously in Fig. 2c).

Singlemode operation was achieved for the design output power (~ 3 dBm out of the 50/50 coupler, Fig. 1) by continuously adjusting the inversion level of the second Er:SiO₂ fiber (Er:SiO₂ #2 in Fig. 1) from an operating regime close to gain saturation ($P_{p2} = 200$ mW, 1.5 μm incident intracavity power ~ 3 dBm) to the saturated absorption regime ($P_{p2} < 50$ mW, 1.5 μm incident intracavity power ~ 3 dBm, absorption saturation powers $P_{\text{sat}} < 0.45$ dBm over this particular P_{p2} pump power range). In effect, the second erbium doped fiber allows for an additional degree of freedom for the control of the laser's desired output characteristics (e.g. output power, singlemode emission) as a function of the intracavity modal losses and gain.

Although not directly demonstrated in the self-heterodyne measurements described above, laser linewidths $\ll 10$ kHz are anticipated (due to the long laser cavity lengths [9]) in the very near future.

WDM channel selection was accomplished easily by tuning the FBG, while observing the laser output power. By monitoring the location of the spectrally tuned output spectra and the Fabry-Perot transmission spectra on an optical spectrum analyzer, we noted that the output power was significantly (about 10 dB) higher when the laser output wavelength was coincident with a transmission peak, as compared to the case when the laser output coincided with one of the Fabry-Perot etalon transmission valleys. Discrete channel selection (at the ITU grid) and singlemode operation is thus obtainable by direct monitoring of just the output power, illustrating the advantage of this source over previous channel-selectable fiber lasers including those based on tunable DFB fiber lasers. In this manner, single-mode channel-selectable WDM laser operation was demonstrated over 8 channels (Fig. 4, optical spectrum analyzer spectra) with 3.10 dBm output powers, ± 0.05 dBm output power uniformities, and

> 50 dB SMSRs (side mode suppression ratios). Although we only tuned our laser over an 8-channel range in the present experiments, stretch-tuning of high-tensile strength FBGs [9] or compressive stress-tuning of conventionally fabricated FBGs [10] should enable tuning of

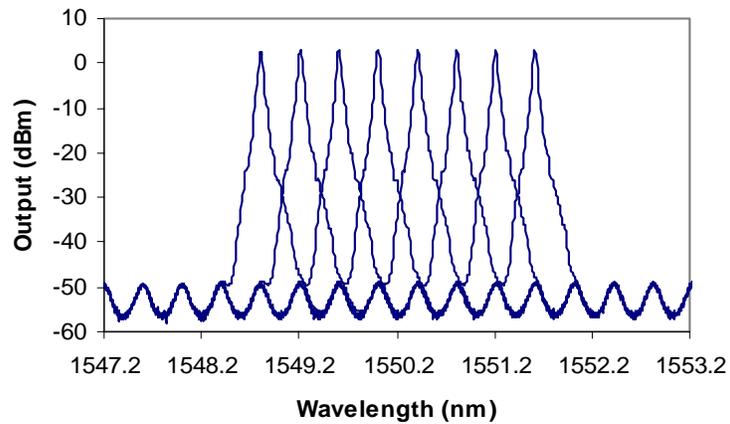


Fig. 4. Tunable WDM outputs at 8 individually-selected channels ($\Delta f = 50$ GHz)
3.10 dBm \pm 0.05 dBm outputs, > 50 dB SMSRs

such fiber lasers over ~ 100 such WDM channels with essentially the same laser architecture. Such *large-channel-count single longitudinal mode channel-selectable fiber lasers with relatively simple channel monitoring demands* appear to hold significant promise for low-noise WDM optical communications systems.