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Citation for the original published paper (version of record):

Yang, X., Lindberg, R., Magrulis, W., Fröjdh, K., Laurell, F. (2019) Continuously tunable, narrow-linewidth laser based on a semiconductor optical amplifier and a linearly chirped fiber Bragg grating Optics Express, 27(10)

Access to the published version may require subscription.

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Continuously tunable, narrow-linewidth laser based on a semiconductor optical amplifier and a linearly chirped fiber Bragg grating

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Abstract: We describe a simple, narrow-linewidth, tunable fiber-based laser with a high degree of tuning accuracy. A polarization independent semiconductor optical amplifier (SOA) is used as the gain medium in a unidirectional fiber ring cavity with a circulator connected to a 6-meter long chirped fiber Bragg grating (CFBG). The laser wavelength is chosen by setting the modulation frequency of the SOA the same as the harmonics of the fundamental repetition rate of the light reflected at a specific point on the CFBG. Careful management of the drive current and pulse width helps to generate laser light of narrow linewidth (less than 0.03 nm) with low power variation (1.46 dB) over a tuning range of 40 nm.

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1. Introduction

Widely tunable laser sources are important tools in a range of scientific and industrial fields. In the near-infrared and mid-infrared spectral regions, they are used in applications such as light detection and ranging (LIDAR) [1], gas sensing [2,3], wavelength division multiplexing [4], and optical coherence tomography [5,6] where the tuning should be fast, stable and accurate. Various methods have been introduced to improve the tuning speed, resolution, and power uniformity over a wide wavelength range. For example, with a sampled grating design, distributed Bragg reflector (DBR) lasers were tuned over the entire telecom C-band using special current management to continuously adjust the wavelength within one channel spacing [7,8]. By exploiting nonlinear effects, wavelength tuning of more than 500 nm was obtained based on optical parametric oscillators [9,10]. Fiber Bragg gratings (FBG), volume Bragg gratings and micro ring resonators have been employed as tunable filters to achieve wider tuning range and higher output power for low-speed tuning [11–15]. Fabry-Perot etalon-based lasers exhibiting excellent tuning speed and range were demonstrated with a fairly simple structure [16–19], where long-term drift of the transmission peak of the etalon was avoided by careful voltage trimming during operation. Fine tuning of less than a 0.1 pm resolution was reported by Hu, et al., using the Vernier effect in a double-ring cavity configuration [20] with sophisticated adjustment of a phase modulator and a polarization controller (PC). While the whole gain band of the semiconductor materials has been exploited for extended tuning range, a simple and fast tunable laser with high tuning precision and stability is still missing.

The concept of electrically programmable laser systems incorporating a highly dispersive cavity and intensity modulation has also been studied for tunable lasers [21–27]. In [21], a 1-cm long chirped fiber Bragg grating (CFBG) was used by Morton et al. as a wavelength selective mirror and dispersion compensator to produce solitons. Li et al. used a 5-mm-long...
CFBG to reach a 7.2-nm continuous tuning range by changing the modulation rate to address a specific region of the grating and at the same time controlling the polarization [22]. With this method, longer CFBGs have been developed and exploited to extend the tuning [23–25] range. Tiess et al. proposed a discretely tuned concept with a step-chirped fiber Bragg grating array [26,27] and demonstrated an ytterbium doped fiber laser with high signal contrast (up to 50 dB) and narrow linewidth (55 pm) over a tuning range of 74 nm.

In this work, we present a continuously tunable laser with great tuning accuracy and power uniformity based on this concept. With the help of a 6-meter-long CFBG and a polarization independent semiconductor optical amplifier (SOA), the laser output has a linewidth of less than 30 pm and a tuning resolution of 3.3 pm with only 1.46 dB power variation over a 40 nm tuning range. The SOA is used as the photon source and its gain is switched on and off at a specific repetition rate, in a highly dispersive cavity, to address a well-defined spectral part of the CFBG, which acts as the wavelength selective element. The output is thereby stably locked to the corresponding wavelength. The laser peak can be continuously tuned thanks to the large chirp and low group delay ripple of the CFBG as well as the low polarization dependent loss of the SOA. Additionally, linewidth narrowing and power flattening over the tuning range is achieved by optimizing the drive current to the SOA.

2. Setup and principle

Figure 1 shows the schematic sigma-cavity laser configuration. The cavity consists of a SOA, a segment of single mode fiber (SMF), a circulator, an output coupler and the CFBG. The semiconductor optical amplifier (SOA1013XS, Thorlabs) serves as the broadband gain medium, as well as the modulator. It is driven by short current pulses of up to 500-mA, providing a maximum pulsed output power of 8 mW. The SOA is polarization independent, which is convenient for achieving fast continuous tuning operation since this eliminates the need for adjusting the polarization with a polarization controller at different wavelengths [22,25]. The SOA has an operating wavelength range from 1528 nm to 1562 nm at 500-mA drive current. The optical pulses from the SOA first travel through a piece of standard single mode telecom fiber (SMF28) with a length of 400 meters, which lowers the fundamental repetition rate of the laser below the frequency limit of our electrical pulse generator (2 MHz). The optical pulses are then coupled through the circulator to the 6-m-long chirped fiber Bragg grating (CFBG model DCMCB, 6 meters, Proximion) with nominal bandwidth from 1526.02 nm to 1573.91 nm. The orientation of the CFBG is arranged in such a way that the near end to the circulator reflects light of longer wavelength while the far end reflects shorter wavelength. The net normal dispersion of the CFBG is measured to be $-1240$ ps/nm, $-1319$ ps/nm, and $-1412$ ps/nm at 1528 nm, 1545 nm and 1565 nm, respectively, with an average value of $-1.3$ ns/nm for the reflection band. A similar dispersion could have been obtained by using an 80-km long standard telecom fiber, but the 6-m-long CFBG makes the cavity length manageable, minimizes nonlinear effects and reduces the loss from $\sim$16 dB to 3.9 dB (CFBG device insertion loss: 2.9 dB), as seen in Fig. 2 (red curve). The 20% port of a fused fiber coupler is used as the laser output, while the remaining 80% re-enters the SOA, where the optical pulses are amplified or absorbed, depending on whether at that time the SOA is electrically pumped or not. The electrical signal on the SOA is provided by the electrical pulse generator (T165-14 Laser Pulser, Highland Technology) with a frequency resolution, a minimum pulse duration and maximum drive current of 1 mHz, 2.2 ns, and 400 mA, respectively.
The large linear chirp introduced by the CFBG considerably alters the round-trip time of optical pulses with different wavelengths. Let $T_o = nL_o/c$ be the shortest time taken for pulses to circulate the cavity, when they are reflected at the nearest end of the CFBG. $n, c$ are the refractive index of fiber and the speed of light in vacuum, respectively. Included in the cavity length $L_o$ are the piece of standard fiber, the SOA, the coupler and the circulator. An additional delay $T_h$ is introduced when a new wavelength is targeted, given by $T_h = Dl[(\lambda - \lambda_o)]$, where $D$ is the average dispersion parameter of the CFBG and $l$ is the extra length on the CFBG, associated to tuning from $\lambda_o$ to $\lambda$. As long as $T_o$ is larger than the maximum of $T_h$, the cavity allows for simple and precise tuning of one single wavelength [22]. Here we chose $T_o \sim 2100$ ns and $T_h$ in the range 0-62.4 ns (corresponding to $L_o = 420$ m and $l = 0-6$ m, respectively). It is clear that continuous adjustment of the SOA drive pulse frequency from $f_0 = 1/T_o$ to $f_h = 1/(T_o + T_h) = 1/[nL_o/c + Dl(\lambda - \lambda_o)]$ leads to univocal wavelength adjustment. Therefore, continuous tuning of the laser spectrum could be realized simply by sweeping the repetition rate of the RF signal driving the SOA.

3. Results and discussion

With a total cavity length of 420 meters, the laser is modulated either at the fundamental order, or at the 2nd, 3rd, 4th harmonics within the 2 MHz limit of the RF pulse generator. The laser is continuously tuned over about 48 nm, from 1526.02 nm to 1573.91 nm, by changing the modulation frequency from 0.463 to 0.477 MHz, 0.926-0.954 MHz, 1.388-1.434 MHz, or
1.852-1.908 MHz. Modulating the SOA at higher harmonics than the fundamental frequency of the cavity makes the laser operate with a number of interleaved combs (trains) of pulses and results in increased average power. Since the gain recovery of the SOA (~ns) is much faster than the repetition rate of the laser at all frequencies studied (~µs), the interleaved combs do not affect each other, and all laser pulses have similar spectral and temporal characteristics. An example of wavelength sweeping is illustrated by the black curve in Fig. 2, when operating the laser at the 3rd harmonic. The peak-holding function of the optical spectrum analyzer (OSA) was used and the multi-peak structure is attributed to the slow scan speed of the OSA. The drive current was in this case 195 mA. The round-trip time difference between the shortest and the longest wavelengths can be calculated by the difference of the modulation period: (1/463.008 kHz) - (1/477.277 kHz) = 64.6 ns, which is reasonable compared with the estimated maximum delay time introduced by the CFBG, 62.4 ns.

Characterization of the spectrum linewidth for different pulse lengths and drive currents is presented in Fig. 3. The resolution of the OSA and RF frequency were set to 0.1 nm and 469.777 kHz respectively, in both cases, which set the laser wavelength to 1550 nm at threshold. As the drive pulses were extended from 2.2 ns to 22.4 ns with drive current fixed at 175 mA, the laser emission red-shifted and the linewidth increased from 0.1 nm to 0.4 nm as shown in Fig. 3(a). Large drive current also gave rise to a striking asymmetric broadening of the spectrum. As can been seen in Fig. 3(b) with the length of the drive pulse fixed at 2.2 ns, increasing the drive current from 175 mA to 225 mA not only broadened the 3-dB linewidth from 0.1 nm to 0.2 nm, but also red shifted the spectral peak. As the drive current was increased further to 300 mA and 375 mA, the larger spectral broadening at longer wavelengths was accompanied by a small blue-shifted tail as well.

The temporal properties of the output pulses and the driving current were also characterized. Driven by electrical pulses of different durations in Fig. 3(c), the optical pulses have similar but slightly shorter profile than the corresponding electrical pulses, as presented in Fig. 3(d). The electrical pulse generator produced a large spike at the leading edge of the electrical pulses as seen in Fig. 3(c), which had little effect on the performance of the optical pulses.

From the discussion above it is clear that low pump levels and narrow drive pulses should be considered to limit the linewidth. In our set-up, this is achieved by the settings of a drive current no larger than 195 mA and a pulse duration of 2.2 ns (shortest available), respectively.
A typical spectrum when operating with these parameters (drive current set to 195 mA) is depicted in Fig. 4 with a higher OSA resolution of 0.01 nm. The excellent long-term stability of our source is also indicated in Fig. 4 by overlapping spectra that were measured 60 minutes apart. The obtained 3-dB linewidth of less than 0.03 nm is, to the best of our knowledge, the narrowest achieved in this type of laser configuration by far. We remark that a single-pass 2.2 ns pulse window corresponds to a spectral width 1.43 nm, almost 50 times wider than the 30 pm measured under lasing conditions and repetitive roundtrips.

The electrical wavelength adjustment is highly accurate, stable and fast compared to wavelength fine-tuning that relies on PC adjustment. This is illustrated in Fig. 5(a) for a tuning step of 0.05 nm (14 Hz of frequency increments). With even finer frequency adjustment, continuous tuning of the wavelength is analyzed based on a tuning spectrogram as depicted in Fig. 5(b), zoomed in on a narrow tuning range. Spectrum at each modulating frequency, separated by 3.3 pm (1 Hz frequency increment), was recorded in a column with color representing the intensity, on a logarithmic dB-scale. The spectral peak is traced by the white line on the peak of the spectrogram. The good linearity between the tuning peak and the modulation frequency indicates a very small group delay ripple of the CFBG, which allows smooth tuning operation. In our case, since the pulse generator can handle frequency variation as small as 1 mHz, the wavelength tuning steps are as fine as 3.3 fm. However, the OSA used in these experiments could not have resolved the stepwise shift in that case. The high tuning resolution is mainly attributed to the large linear chirp of the CFBG.
Comparing the power variation performance reported in previous work [24,25] to what we present here gives a clear picture of how polarization dependent loss, which we avoided substantially by employing a polarization independent SOA, impacts the power flatness. However, to achieve a stable output level across the entire tuning range, the pulse current must be set appropriately. This is illustrated by the wavelength sweeps at 220mA, 195 mA, and 170 mA drive current to the SOA while having a fixed drive pulse width of 2.2 ns, in Figs. 6(a)-6(c), respectively. The frequency change was set to 1 kHz while the laser was modulated at the fundamental repetition rate. The output power flatness over 40 nm tuning range was measured to be 1.15 dB, 1.46 dB and 5.78 dB, while the spectral linewidth was measured to be 0.08 nm, 0.03 nm, and 0.03 nm, respectively. Note that the 8-nm spectral part at the longer wavelength end of the CFBG (> 1566 nm) was not utilized in the measurement because the gain from the SOA is quite low in this region, as seen in Fig. 6(b). There is evidently need for optimization of the drive pulses to achieve narrow linewidth and low power variation over a wide tuning range simultaneously. For our laser setup, a drive current of 195 mA and 2.2 ns modulating pulse width gave 0.03 nm linewidth, 1.46 dB power variation with 3.3 pm tuning resolution over the 40-nm wide tuning range. With these settings, the output power and the signal-to-noise ratio (SNR) were −26 dBm and 28 dB, respectively. These can be further improved either by an amplifier or by modulation at higher harmonic frequencies. Since this demonstration covers more than the telecom C-band, a judicious choice of commercial components is needed for even better performance, for example by using flat response fused couplers and circulators.

![Fig. 6. Wavelength sweep with a drive current of (a) 220 mA, (b) 195 mA, and (c) 170 mA.](image)

To illustrate our laser’s readiness for applications, we performed a simple spectroscopic measurement on the absorption lines of acetylene around 1540 nm. Light from our tunable laser was coupled through a 1.3-m long piece of hollow-core anti-resonant fiber that had been filled with a small amount of acetylene gas mixed with air at atmospheric pressure. The absorption of the main vibrational lines at around 1530 nm was so strong that the peaks appeared saturated. Choosing to study the absorption at a wavelength range away from the strongest absorption allowed us to check the laser performance as a high-resolution spectral interrogator. The result of such a measurement without averaging is displayed in Fig. 7 (black solid line). Good agreement is found with the expected signal from the simulation (with a volume mixing ratio of about 0.58) based on data from the HITRAN database (red dashed line).
4. Conclusion

We demonstrate a simple, stable and continuously tunable fiber-integrated laser with 40 nm tuning range, less than 0.03 nm linewidth and a high wavelength tuning accuracy. It follows the design of a modulated dispersive cavity and has greater spectral properties thanks to a 6-meter-long chirped FBG and a polarization insensitive SOA. The SOA is used as the gain media and modulator at the same time, which greatly simplifies the design and reduces the cost of the laser. By modulating the drive pulse to the SOA at a fixed repetition rate, the wavelength is locked precisely. A 3.3 pm tuning resolution was demonstrated, and even finer stepwise adjustment is inferred. Narrow linewidth and flat output power over the entire tuning range were also achieved by adjusting the pumping current to the SOA. These are attractive features for applications relying on tunable sources. Furthermore, we believe that the performance can be improved even more by using narrower modulating pulses, a faster SOA and flat spectral response components.

It is difficult to check all the boxes for a perfect tunable laser while keeping the system simple and cost effective. Nevertheless, our work provides favorable spectral performance in terms of linewidth, power variation, stability, tuning accuracy and tuning range at the same time.

Funding

K. A. Wallenberg Foundation, the Swedish Foundation for Strategic Research, and China Scholarship Council.

Acknowledgments

We would like to acknowledge Carolina Franciscangelis, Frans Forsberg and Kenny Hey Tow from RISE Acreo, Sweden for technical and moral support.

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