High-speed wavelength-swept semiconductor laser with a polygon-scanner-based wavelength filter

S. H. Yun

Harvard Medical School and Wellman Laboratories for Photomedicine, Massachusetts General Hospital, 50 Blossom Street, BAR 718, Boston, Massachusetts 02114

C. Boudoux

Harvard–MIT Division of Health Sciences and Technology and Department of Nuclear Engineering, Massachusetts Institute of Technology, Wellman Laboratories of Photomedicine, 50 Blossom Street, BAR 710, Boston, Massachusetts 02114

G. J. Tearney and B. E. Bouma

Harvard Medical School and Wellman Laboratories for Photomedicine, Massachusetts General Hospital, 50 Blossom Street, BAR 703, Boston, Massachusetts 02114

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Ultrahigh-speed tuning of an extended-cavity semiconductor laser is demonstrated. The laser resonator comprises a unidirectional fiber-optic ring, a semiconductor optical amplifier as the gain medium, and a novel scanning filter based on a polygonal scanner. Variable tuning rates up to 1150 nm/ms (15.7-kHz repetition frequency) are demonstrated over a 70-nm wavelength span centered at 1.32 μm. This tuning rate is more than an order of magnitude faster than previously demonstrated and is facilitated in part by self-frequency shifting in the semiconductor optical amplifier. The instantaneous linewidth of the source is <0.1 nm for 9-mW cw output power and a low spontaneous-emission background of -80 dB. © 2003 Optical Society of America

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Considerable effort has recently been devoted to the development of rapidly scanning, widely tuning laser sources for optical reflectometry, biomedical imaging, sensor interrogation, and test and measurement applications.[1–8] The commonly used technique for fabricating such lasers is to employ an intracavity narrowband wavelength-scanning filter. Mode-hopping-free single-frequency operation has been demonstrated in extended-cavity semiconductor lasers with sophisticated grating fiber designs. However, the tuning speed demonstrated so far has been limited less than 0.1 nm/ms.[8] For several applications, single-frequency operation is not essential and can be compromised to enhance tuning speed. An instantaneous linewidth of 10 GHz is sufficiently narrow to provide useful ranging depth of a few millimeters in optical coherence tomography[5,6] or micrometer-level transverse resolution in spectrally encoded confocal microscopy.[9] Linewidths of the order of 0.1 nm and wide sweep ranges (30–100 nm) have been demonstrated by use of rapidly tuning elements such as acousto-optic filters, Fabry–Perot filters, and rotating-mirror grating filters.[1–7] However, the maximum sweep frequency of these lasers has been less than 1 kHz. Significantly higher-speed tuning is required for video-rate (>30 frames/s) high-resolution optical imaging in biomedical applications.[10] In this Letter we demonstrate an ultrahigh-speed wavelength-swept laser with a tuning speed as fast as 1150 nm/ms and a variable repetition rate as high as 15.7 kHz, an order of magnitude faster than previously demonstrated. An enabling component of this laser is a novel wavelength-scanning filter based on a polygonal scanner and diffraction grating.

A schematic of the wavelength-scanning filter is presented in Fig. 1. The reflection-type filter comprises a diffraction grating, an afocal telescope, and a polygonal scanner. The telescope is made from two lenses in an infinite-conjugate configuration with the grating at the front focal plane of the first lens (Lens 1) and the polygonal spin axis at the back focal plane of the second lens (Lens 2). The telescope serves two distinct roles: It converts diverging angular dispersion from the grating into converging angular dispersion after the second lens and controls the imaged beam size and convergence angle at the polygon. As is illustrated in Fig. 1, the polygon reflects back only the spectral components within a narrow resolution band normal to the front mirror facet of the polygon. The reflected component is dispersed again on the second

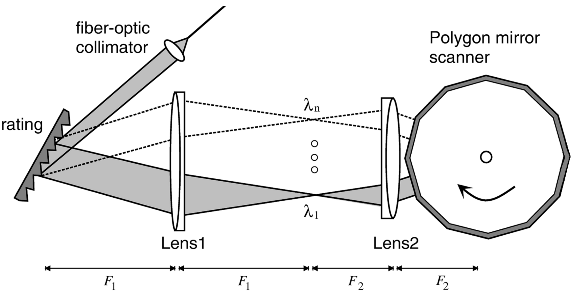

Fig. 1. Schematic of high-speed wavelength-scanning filter.

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diffraction at the grating and is received by the optical fiber. The orientation of the beam's incidence angle and the rotation direction of the polygonal mirror determine the direction of wavelength tuning. The arrangement in Fig. 1 produces a positive (increasing wavelength) sweep.

Consider a Gaussian beam with a broad optical spectrum incident onto the grating from the fiber collimator. The well-known grating equation[11] is expressed as $\lambda = p(\sin\alpha + \sin\beta)$, where λ is the optical wavelength, p is the grating pitch, and α and β are the incident and the diffracted angles of the beam, respectively, with respect to the normal axis of the grating. The center wavelength of the tuning range of the filter is given by $\lambda_0 = p(\sin\alpha + \sin\beta_0)$, where β_0 is the angle between the optical axis of the telescope and the grating normal. It can be shown that the FWHM bandwidth of the filter is given by $(\delta\lambda)_{\mathrm{FWHM}}/\lambda_0 = A(p/m)\cos\alpha/W$, where $A = \sqrt{4\ln 2/\pi}$ for a double pass, m is the diffraction order, and W is the $1/e^2$ width of the Gaussian beam at the fiber-optic collimator.

The tuning range of the filter is fundamentally limited by the finite numerical aperture of the first lens. The acceptance angle of that lens is given by $\Delta\beta = (D_1 - W\cos\beta_0/\cos\alpha)/F_1$, where D_1 and F_1 are the lens's diameter and focal length, respectively. From the acceptance angle, the filter tuning range is given by $\Delta\lambda = p\cos\beta_0\Delta\beta$. A spectral component after propagating through both lenses will have a beam propagation axis at an angle β' with respect to the optical axis: $\beta' = -(\beta - \beta_0)(F_1/F_2)$, where the minus indicates that the diverging angular dispersion is transformed to converging dispersion. The polygon has a facet-to-facet polar angle given by $\theta = 2\pi/N \approx L/R$, where N is the number of facets, L is the facet width, and R is the radius of the polygon. If the angular range of the spectrum incident upon the polygon is greater than the facet angle, i.e., $\Delta\beta' = \Delta\beta(F_1/F_2) > \theta$, the polygonal mirror can retroreflect more than one spectral component at a given time. The spacing of these spectral components, or the free spectral range (FSR) can be shown to be $(\Delta\lambda)_{\mathrm{FSR}} = p\cos\beta_0(F_2/F_1)\theta$. For a homogeneously broadened gain medium, the tuning range of the laser cannot exceed the free spectral range of the filter. The duty cycle of laser tuning can be 100% if two necessary conditions are met: $(F_2 - S)\theta + W' < 2L$ and $(F_2 - S)\theta - W' > 0$, where $W' = W(\cos\beta/\cos\alpha)(F_2/F_1)$ is the beam size at the polygonal mirror and S is the distance between lens 2 and the front mirror of the polygon. These relations are derived from the condition that all the beams within the spectral tuning range should fall within a mirror facet without clipping. It follows from the relations that $W' < L$.

In the experiment we selected optical components with the following parameters: $W = 1.9$ mm, $p = 1/1200$ mm, $\alpha = 1.2$ rad, $\beta_0 = 0.71$ rad, $m = 1$, $D_1 = D_2 = 25$ mm, $F_1 = 100$ mm, $F_2 = 45$ mm, $N = 24$, $R = 25$ mm, $S = 20$ mm, $\theta = 0.26$ rad, and $\lambda_0 = 1320$ nm. With these parameters the theoretical FWHM bandwidth, tuning range, and FSR of the filter are $(\delta\lambda)_{\mathrm{FWHM}} = 0.11$ nm, $\Delta\lambda = 126$ nm, and $(\Delta\lambda)_{\mathrm{FSR}} = 74$ nm. The two conditions for 100% duty cycle were satisfied with margins. Figure 2 shows the measured characteristics of the filter. The efficiency of the filter, shown by curve (a), was measured by use of spontaneous-emission light from a semiconductor optical amplifier (SOA) and an optical spectrum analyzer in peak-hold mode while the polygonal mirror was spinning at its maximum 39,325 rpm, producing a sweep repetition rate of 15.73 kHz. The measured tuning range was 90 nm, which is substantially smaller than the theoretical value of 126 nm. We attribute this discrepancy to aberration in the telescope, primarily in field curvature, which can be improved by use of optimized lenses. Curve (b) of Fig. 2 shows the throughput spectrum when the polygonal mirror was static at a particular position. The FSR was 73.5 nm, in agreement with the theoretical calculation. The FWHM of the filter passband was measured to be 0.12 nm, corresponding to the predicted 0.11 nm.

The polygon-based filter was incorporated into an extended-cavity semiconductor laser via a Faraday circulator, as shown in Fig. 3. The gain medium was a SOA (Philips CQF 882/e), and the laser output was obtained through the 90% port of a fiber-optic fused coupler. To generate a synchronization signal (Sync), we directed 10% of the laser output was to a photodetector through a variable-wavelength filter with a bandwidth of 0.12 nm. The detector signal generated short pulses when the output wavelength of the laser was swept through the narrow transmission band of the

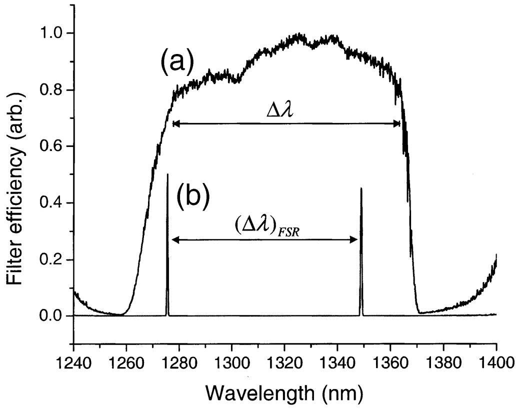


Fig. 2. Throughput (reflected) spectra when the filter was (a) spinning and (b) fixed.

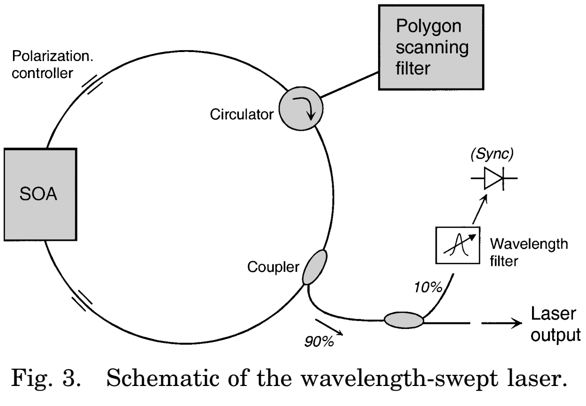
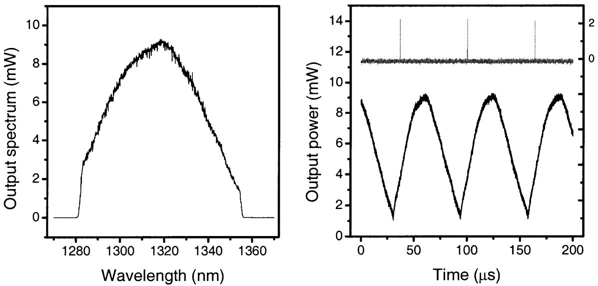


Fig. 3. Schematic of the wavelength-swept laser.



(a) (b)

Fig. 4. (a) Time-averaged output spectrum and (b) oscilloscope trace of the laser output.

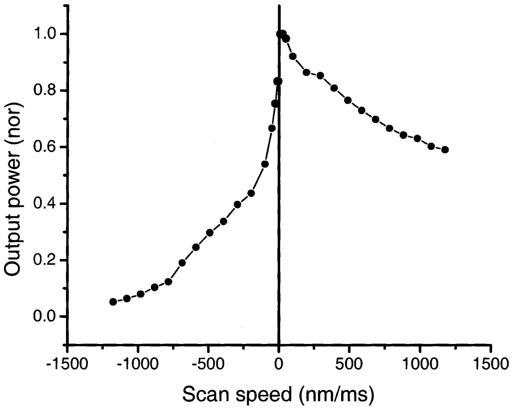


Fig. 5. Peak output power measured as a function of scan speed.

fixed-wavelength filter. Figure 4(a) shows the output spectrum of the laser measured with an optical spectrum analyzer in peak-hold mode. The edge-to-edge sweep range was 73 nm wide (1282–1355), matching the FSR of the filter. The Gaussian-like profile of the measured spectrum was due mainly to polarization-dependent cavity loss caused by polarization sensitivity of the filter and birefringence in the cavity. It was necessary to adjust intracavity polarization controllers to obtain maximum sweep range and output power. Figure 4(b) shows the laser output in the time domain. The upper trace is the sync signal obtained through the fixed-wavelength filter. Power fluctuation from facet to facet was less than 2.3% and during one revolution of the polygon did not exceed 3.5%. The peak and the average output power was 9 and 6 mW, respectively. The instantaneous linewidth was determined to be <0.1 nm from the measurement of coherence length of the output by use of a variable-delay Michelson interferometer. The spontaneous-emission noise level relative to the peak of the laser spectrum was −80 dB, measured while the polygon mirror was fixed.

As was demonstrated recently,[12] the SOA's gain medium produces a frequency downshift of the intracavity laser spectrum through intraband four-wave mixing. Scanning the filter in the same direction as the frequency shift allows intracavity light to experience less loss and results in a higher power. Figure 5 shows the peak power of the laser output measured as a function of tuning speed. We obtained the negative tuning speed by flipping the position of the collimator and the orientation of the grating with respect to the optic axis of the rest of system. Care was taken to make the conditions of the filter and laser cavity, except for the tuning direction, identical in both cases. The result shows that the combined action of the frequency shift and positive tuning allows higher output to be obtained and enables the laser to be operated at higher tuning speed.

In conclusion, we have presented the design principles of a polygonal scanner-based wavelength-scanning filter and have demonstrated the application of this filter to high-speed tuning in an external-cavity semiconductor laser. Scanning rates as fast as 1150 nm/ms were demonstrated at scan frequencies as high as 15.7 kHz. The frequency shift in the SOA gain medium was advantageously used in conjunction with positive wavelength tuning to optimize power and tuning speed.

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