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115 kHz tuning repetition rate ultrahigh-speed wavelength-swept semiconductor laser

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Abstract

We demonstrate an ultrahigh-speed wavelength-swept semiconductor laser using a polygon-based wavelength scanning filter. With a polygon rotational speed of 900 revolutions per second, a continuous wavelength tuning rate of 9200 nm/ms and a tuning repetition rate of 115 kHz were achieved. The wavelength tuning range of the laser was 80 nm centered at 1325 nm, and the average polarized output power was 23 mW.

Rapidly swept continuous-tuning lasers have become important light sources for a number of applications, including reflectometry, grating interrogation, and biomedical imaging.[1–5] A high repetition rate of tuning is highly desirable, in particular, for optical frequency-domain imaging (OFDI) in biomedical applications, because the sweep rate determines the A-line acquisition rate and, therefore, imaging speed.[5] While significantly improved imaging rates have been demonstrated with OFDI,[5,6] realizing the full potential of this technology for high-speed imaging will require advances in wavelength-swept lasers. Recently a wavelength-swept laser with an unprecedentedly high repetition rate of 15.7 kHz and a wavelength sweep range of over 73 nm centered at 1.3 μm was demonstrated.[7] The rapid wavelength sweep was accomplished by use of an intracavity wavelength filter based on a polygonal mirror scanner. For this filter, one complete wavelength sweep was produced for each partial rotation of the polygon through an angle of $2\pi/N$, where N was the number of mirror facets. The characteristic tuning repetition rate of the laser was therefore determined by the product of the rotational speed and the number of facets of the polygon. The most straightforward way to increase the tuning speed without changing the filter configuration would be to simply increase the rotational speed of the polygon. Mechanical considerations, however, ultimately limit this approach, and significant improvements over previous designs are not feasible. Increasing the number of polygon facets also has a limitation. In OFDI, the finesse of the laser's spectral emission determines the ratio of the ranging depth to the resolution; to achieve high resolution and large ranging depth the laser spectrum must have a high finesse. Since the finesse of the polygon-scanning filter was proportional to the facet-to-facet angle of the polygon, increasing the number of mirror facets would decrease the finesse of the filter and compromise OFDI performance. In this Letter, we describe novel configurations for the polygon-scanning filter that overcome these limitations and demonstrate a wavelength tuning repetition rate of 115 kHz while maintaining a sufficiently high finesse for large ranging depth and high-resolution OFDI.

The previously published polygon filter design comprised a fiber optic collimator, a diffraction grating, a telescope to invert the angular dispersion from the grating, and a polygonal mirror to retroreflect light back through the optical system to the collimator. By positioning the

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polygon spin axis at the center of the image plane of the telescope, the surface normal of each facet determined the wavelength selected on reflection. Three novel filter configurations, depicted in Fig. 1, overcome the scanning repetition-rate limitation of the previous design through the utilization of multiple reflections from the polygon. Considering the design depicted in Fig. 1(a), the polygon has been moved away from and off the axis of the telescope so that the mirror facet is at the image plane, and a planar mirror has been added as an end reflector. In this case, the sweep angle of the reflected light from the polygon mirror is double the polygon's rotation angle. Since the free spectral range (FSR) of the filter is proportional to the sweep angle, the FSR will be twice that for the case when the polygon simply retroreflects the light back to the telescope. Although increasing the FSR may be important for certain applications, an alternative would be to double the number of facets on the polygon, thereby maintaining a constant FSR but doubling the wavelength scanning speed and the repetition rate.

In contrast with the design of Fig. 1(a), an alternative approach to increasing the scanning repetition rate while not requiring higher facet density is depicted in Fig. 1(b). In this design, two planar end reflectors are employed with a relative angle equal to the polygon facet-to-facet angle, θ'. This arrangement allows two wavelength sweeps to be made while the polygon is rotated through angle θ'. For a polygon with the same number of facets as in the previous filter design,[7] the two-end-reflector scheme would provide an identical FSR but a wavelength scanning repetition rate that is twofold greater. The tuning repetition rate can be further increased, by a factor of M, through the use of M end reflectors. In this case, however, the FSR would be reduced by a factor $2/M$. To obtain uniform wavelength sweeps in this configuration, the end reflectors must be accurately aligned with a constant interval of angular separation.

The performance improvements described above for the double-pass configurations can be extended by increasing the number of reflections from the polygon. Figure 1(c) depicts a configuration in which light reflected from the polygon is redirected, via a 1:1 folded telescope, to illuminate another mirror facet prior to retroreflection into the laser. For a polygon with the same number of facets as in the previous filter design, this design would yield an increase in the FSR by a factor of 4. Alternatively, a polygon having four times more facets than that used in the previous scheme[7] would yield an equivalent FSR but would increase the tuning speed and repetition rate fourfold. In practice, the FSR increase is ultimately constrained by the facet-size reduction since the magnification of the telescope needs to be adjusted to match the beam size to the facet size.

The filter design depicted in Fig. 1(c) was constructed using a custom polygon-scanning mirror with 128 facets, corresponding to θ=2.81°, and individual facet widths of 1.56 mm. The rotational rate of the polygon could be continuously adjusted up to a maximum speed of 900 revolutions per second, corresponding to a filter repetition rate of 115.2 kHz A telescope comprising a pair of achromatic lenses with F_1=100 mm and F_2=25 mm was placed between a diffraction grating and the polygon mirror. The focal lengths of the telescope lenses were chosen to produce a $1/e^2$ beam width of 1.86 mm (3 dB beam width of 1.09 mm) on the polygon mirror, slightly larger than the facet width. Using a relatively low-groove-density blazed diffraction grating (600 lines/mm) reduced the field curvature aberration in the telescope.[8] A folded telescope, comprising two identical 60 mm focal-length achromatic lenses and two mirrors, M_1 and M_2, redirected the light from the polygon to a second facet at a separate location on the polygon mirror. An end reflector, M_3, was used to retroreflect light back to the incident path and subsequently back into the laser cavity. The FWHM bandwidth of the filter, measured with an optical spectrum analyzer, was 0.16 nm, slightly broader than the theoretical value of 0.15 nm. We attribute this slight discrepancy to the mismatch between the facet size and the optical beam size at the polygon. The measured FSR of the filter was 80.3 nm, in good correspondence with the theoretical value of 80.4 nm. For comparison, the previous filter design,[7] using the same diffraction grating, telescope and polygon, would yield a FSR of 20.1 nm.

To test the tuning performance of this filter, a unidirectional fiber-optic resonator was constructed (Fig. 2). A broad-bandwidth semiconductor optical amplifier (Covega BOA1017) was used as the gain medium for the laser and was coupled to the filter via an optical circulator. Semiconductor optical amplifiers are well suited for high-speed wavelength tuning because of their high gain, robustness, and fast gain response characteristics. A 50/50 fiber optic coupler, positioned after the amplifier, functioned as an output coupler for the cavity. Time-averaged spectra emitted from the laser were acquired using an optical spectrum analyzer in peak-hold mode. The instantaneous line-width was characterized for various polygon rotational speeds by use of a variable-delay Michelson interferometer, external to the cavity, to measure the coherence length of the laser emission. At a tuning repetition rate of 32 kHz, these measurements yielded an instantaneous linewidth of 0.16 nm. Although the filter tuning was in the same direction as the self-frequency shift occurring in the amplifier (short wavelength to long wavelength),[7] operating the filter at faster speeds resulted in an increased linewidth and a decreased coherence length. To reduce this effect, a shorter cavity round-trip path length is desirable to obtain the smallest possible offset of the filter center wavelength per round trip.[9] The round-trip optical path length of the laser cavity used in this demonstration was 5.2 m, including a 1.3 m round-trip path in the filter and a 3.9 m path through the fiber ring cavity and amplifier.

Figure 3(a) depicts the laser output power measured over the course of four wavelength scans while the polygon scanner was operated at its maximum rotational rate. The observed scan duration of 8.7 μs and 100% duty cycle correspond to a repetition rate of 115 kHz. The peak power and the average power emitted by the laser were 31.2 and 23.3 mW, respectively, and the instantaneous linewidth was 0.23 nm. Although this linewidth is broadened relative to that for slower tuning speeds, a biologically relevant ranging depth of 3.3 mm could still be achieved in OFDI systems with frequency shifting.[10] The solid black curve of Fig. 3(b) shows the integrated laser output spectrum and demonstrates the 80 nm edge-to-edge tuning range of the laser (67 nm at 3 dB), in good correspondence to the FSR of the filter. For comparison, the filter was reconfigured, using the same optical components, to represent the previous design.[7] In this case the wavelength tuning range, depicted by the gray curve in Fig. 3(b), was found to be 21 nm. Using the filter design of Fig. 1(a), we observed a tuning range of 42 nm [dashed curve, Fig. 3(b)].

In conclusion, broadly tunable, high-speed wavelength-swept lasers are important for many applications including medical imaging. We have described novel tunable optical filters based on multi-faceted polygon scanners and have demonstrated their use for ultrahigh-speed and ultrahigh-repetition-rate operation of a wavelength-swept semiconductor laser. The observed tuning velocity of 9200 nm/ms is, to our knowledge, the fastest laser tuning speed achieved to date and may enable image acquisition rates in OFDI greater than 200 frames per second.

Acknowledgments

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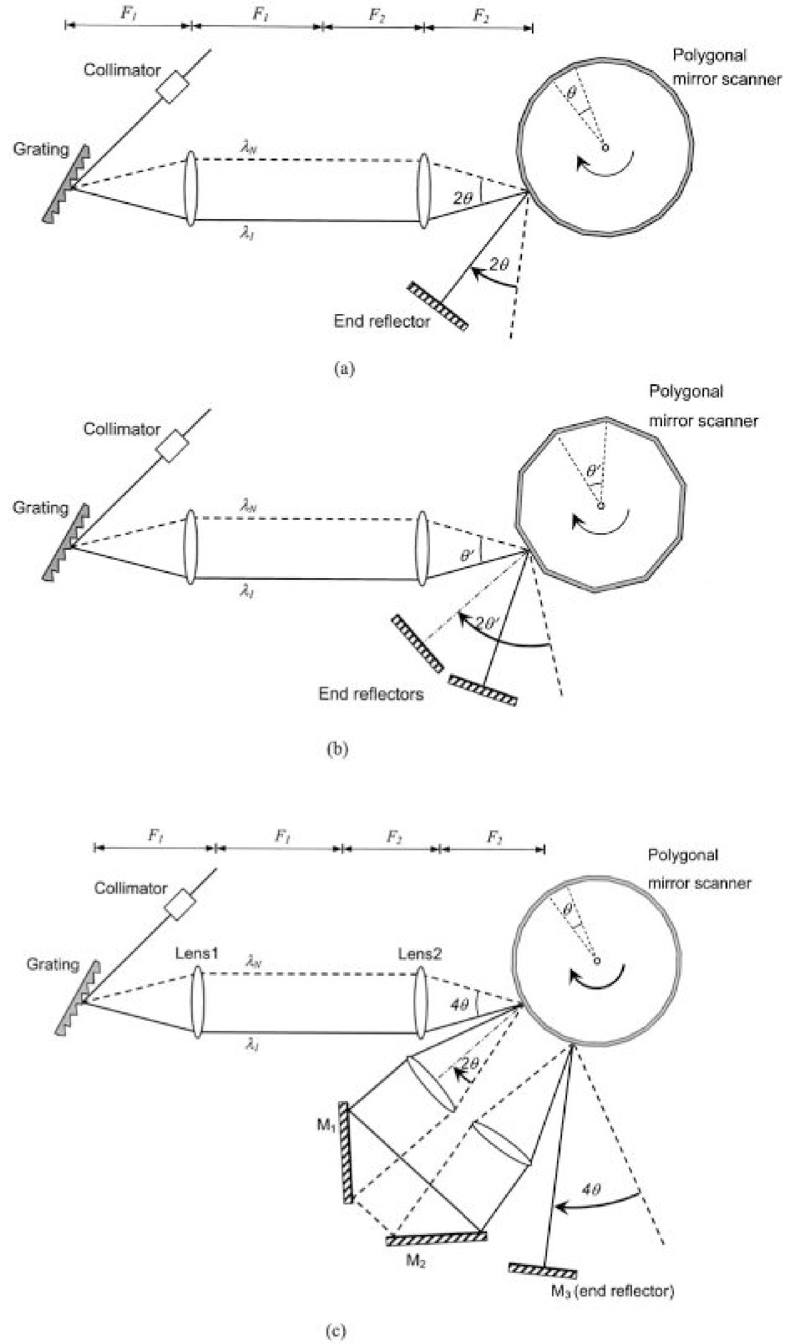

Fig. 1.

Schematics of polygon-scanning filter operation. (a) Filter configuration for doubling either the FSR or the wavelength scanning speed. (b) Filter configuration allowing two wavelength sweeps during one polygon facet-to-facet angle rotation by using two end reflectors. (c) Polygon filter configuration for the wavelength sweep rate of 115 kHz.

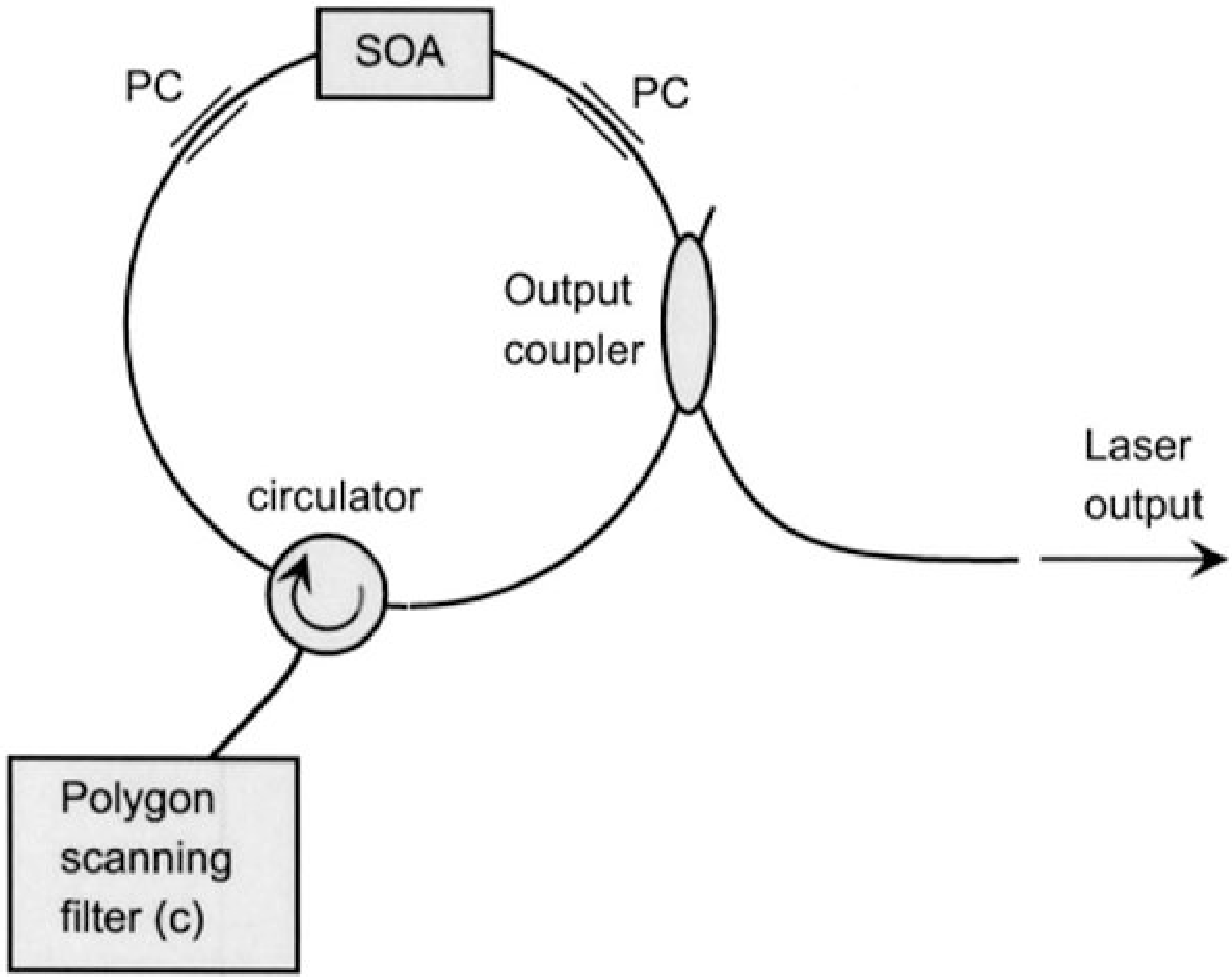

Fig. 2.
Schematic of the wavelength-swept laser with the polygon-scanning filter of Fig. 1(c): SOA, semiconductor optical amplifier; PCs, polarization controllers.

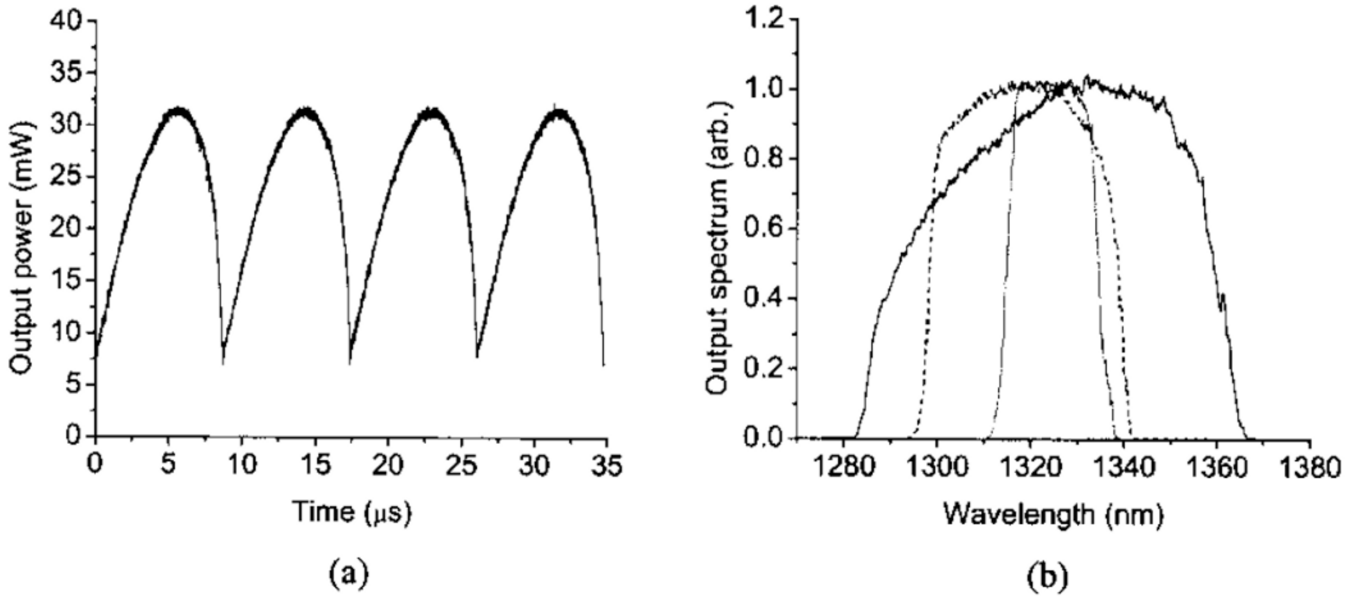

Fig. 3.
(a) Oscilloscope trace of the laser output, showing four tuning cycles at a repetition rate of 115 kHz. (b) Integrated laser output spectrum. Solid black curve, laser output with the proposed polygon-scanning filter of Fig. 1(c) for a 115 kHz tuning repetition rate. Gray curve, laser output with the previous filter design[7] using the same optical components. Dashed curve, laser output with the filter design of Fig. 1(a) using the same optical components.