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A NOVEL SWEPT LASER SOURCE BASED ON COMBINED TUNABLE FILTERS FOR OCT

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A novel broad tunable bandwidth and narrow instantaneous line-width linear swept laser source using combined tunable filters working at 1,300 nm center wavelength is proposed. The combined filters consist of a fiber Fabry−Perot tunable filter and a tunable filter based on diffractive grating with scanning polygon mirror. In contrast to traditional method using single tunable filter, the trade-off between bandwidth and instantaneous line-width is alleviated. Parallel implementation of two semiconductor optical amplifiers with different wavelength range is adopted in the laser resonator for broadband light amplification. The Fourier domain mode locking swept laser source with combined tunable filters offers broadband tunable range with narrow instantaneous line-width, which is especially benefiting for high-quality optical frequency domain imaging. The proposed Fourier domain mode locking swept laser source provides a tuning range of 160 nm with instantaneous line-width of about 0.01 nm at sweeping rate of 15 kHz, a finesse of 16,000 is thus achieved.

Keywords: Swept laser source; tunable filter; optical frequency domain imaging.

1. Introduction

Optical coherence tomography (OCT) combines advantages of confocal, low coherence, optical heterodyne detection, and scanning tomography, and realizes noninvasive and *in vivo* measurement. It enables micron-scale, cross-sectional, and three-dimensional (3D) imaging of biological tissues *in situ* and in real time. The technique measures the echo time delay and intensity of backscattered light using interferometry with broadband light sources or with frequency swept lasers. The approach is analogous to ultrasound, except that imaging is performed by measuring light rather than sound.[1−3] Of particular interest is the technique of swept-source OCT, also called optical frequency domain imaging (OFDI) based on frequency swept laser source.[4−6] A broadband laser source is optically filtered such that the wavelength that interacts with the sample is swept linearly in time. The imaging quality of OFDI depends to a great extent on the swept laser source, which is expected to be high-speed linear scan, broad tunable range, narrow instantaneous line-width, high output power.

Since 1997 Chinn *et al.* first obtained the OFDI images of a sample of glass cover slips using a grating-tuned external cavity swept laser with a peak gain at 840 nm,[7] OFDI has generated considerable interests and is growing rapidly.[8] Swept laser source is realized

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that spontaneous emission light of the gain medium is dispersed in time domain by tunable filter and is amplified in the laser cavity, so periodic time encoded spectra are obtained. The recent introduction of Fourier domain mode locking (FDML)[9–11] has helped to overcome physical limitations of rapid wavelength swept laser sources. With sweep repetition rates of more than 370 kHz, FDML lasers are the light source of choice for many biomedical imaging and sensing applications.[12–14] FDML lasers have enabled unprecedented imaging rates for densely sampled volumetric datasets, improving the visualization of tissue morphology. In FDML, a narrowband optical bandpass filter is driven in resonance with the optical roundtrip time of the laser cavity. For sweep rates in the 100 kHz range, the required resonator length of several kilometers is realized by a long delay line consisting of single mode optical fiber. As each wavelength component circulates in the cavity such that it is transmitted through the filter at every pass, FDML represents a stationary operating regime of lasers. Lasing does not have to build up repetitively as in standard swept laser sources. Compared to standard wavelength swept lasers, FDML lasers exhibit improved noise performance, coherence length, output power, and higher maximum sweep repetition rate. The gain media adopted for both standard swept source and FDML laser are semiconductor optical amplifier (SOA),[9–14] superluminescent LED,[7] tapered amplifier,[15] Erbium-doped fiber amplifier,[16] and Raman fiber amplifier.[17] Since SOA provides vastly high gain and a broad optical gain spectrum, and in addition, can be electrically pumped with a high wall plug efficiency and have a short carrier lifetime to suppress pulsing, therefore SOA is well suited for wavelength swept sources in OCT systems. Tunable filters used are acousto-optic tunable filter,[16] fiber Fabry–Perot tunable filter (FFP-TF),[9–12,17,19] Fabry–Perot electro-optic modulator,[20] grating and scan Galvanometer tunable filter,[7,21,22] grating and polygon mirror tunable filter,[23–25] grating and MEMS scanner mirror tunable filter,[26] and superstructure-grating distributed Bragg reflector.[27] In all these tunable filters, FFP-TF and grating and polygon mirror tunable filter are extensively adopted as the narrowband optical bandpass filter of the swept laser source. To achieve wide tuning range, FFP-TF works at its resonant frequency in the conventional swept light laser, which requires high driven voltage resulting in sinusoidal nonlinear scan. In addition, the repetition rate of the swept source is limited by the resonant frequency. Grating and polygon mirror tunable filter can reach ultrawide tuning range but must compromise requirement of narrow instantaneous line-width. Moreover, it also needs to be limited to the bandwidth of the gain medium.

Characteristic broad bandwidth, narrow instantaneous line-width swept laser source is expected because a wide tuning range is required to achieve high axial resolution in optical imaging and a narrowband spectral filtering is suitable for achieving a large imaging depth range. In the conventional swept light laser using single tunable filter, the trade-off between bandwidth and instantaneous line-width must be considered. It cannot be obtained with broad bandwidth and narrow instantaneous line-width simultaneously. In this study, a novel broad tunable bandwidth and narrow instantaneous line-width FDML swept laser source using combined tunable filters with the center wavelength of 1,300 nm is proposed. The combined tunable filters are composed of FFP-TF and polygon filter based on diffractive grating with scanning polygon mirror in Littrow configuration, which can achieve broad bandwidth and narrow instantaneous line-width simultaneously. Parallel implementation of two semiconductor optical amplifiers whose gain spectra are distinct is adopted in the laser resonator for broadband light amplification. The proposed FDML swept laser source provides a tuning range of 160 nm with instantaneous line-width of about 0.01 nm at a sweeping rate of 15 kHz, a finesse of 16,000 is thus achieved.

2. Theory and Method

The combined tunable filters consist of a FFP-TF and a polygon filter based on diffractive grating with polygon scanner. Figure 1 illustrates the configurable schematic of the polygon filter. The polygon filter is composed of fiber collimator, polygon mirror driven by function generator, and diffractive grating. It is shown that the compact polygon filter in the Littrow configuration does not have a telescope. In this configuration shown in Fig. 1, one facet of the polygon is used and the diffraction grating is illuminated once. The reflected light from the polygon scanner facet illuminates the diffraction grating at Littrow's angle α and retraces the path back to the collimator. The tuning of the filter is

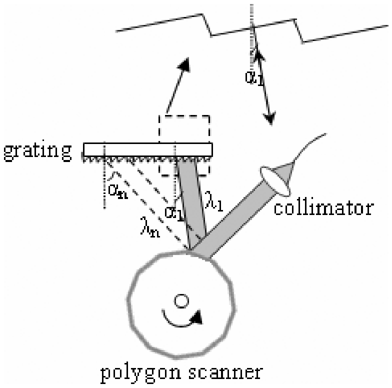

Fig. 1. Schematic diagram of polygon filter based on grating and scanning polygon mirror in Littrow configuration.

accomplished by spinning of the polygon mirror. One complete wavelength sweep (from λ_1 to λ_n) is produced for each partial rotation of the polygon mirror through an angle of $2\pi/N$, where N is the number of mirror facets, while the sweep angle (from α_1 to α_n) of the reflected light is double the polygon mirror's rotation angle ($\varphi = 2\pi/N$). This auto-collimating optical configuration increases the free spectral range (FSR) of the filter through the Littrow illumination. Since the FSR of the filter is proportional to the sweep angle, and the sweep angle of the reflected light from the polygon mirror is double the polygon's rotation angle in this configuration, the FSR will be twice that for the case when the light illuminates a grating and passes through a telescope, and the polygon simply retro-reflects the light back to the telescope.[23]

Collimator (OFR Inc., $f = 1.0$ mm, best collimation distance: 1−20 cm) is placed at the position from polygon mirror about 12 cm within best collimation distance. The polygon mirror is driven by TTL pressure from a function generator, so it can rotate at arbitrary speed as long as it spins within the maximum rate. The diffraction grating (Newport Inc., 400 lp/mm, 30 mm × 30 mm) is placed close to the polygon scanner (Lincoln Laser Inc., 72 facets; facet length: 2.77 mm; facet thickness: 6.35 mm) facet (about 3 cm) to decrease beam displacement on the diffraction grating. The polygon filter can obtain ultrawide tunable range.

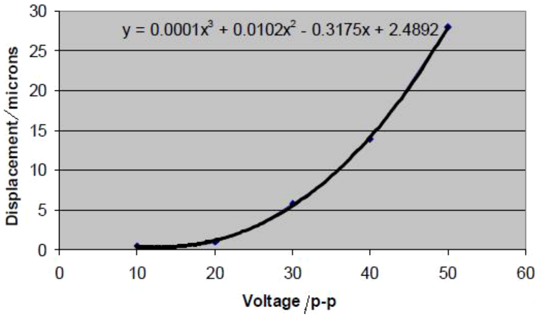

Fig. 2. Actuator displacement versus voltage of FFP-TF driven at 1 kHz.

Figure 2 shows piezoelectric actuator displacement varying with voltage of FFP-TF driven at 1 kHz. The FFP-TF is an all-fiber device having a cavity formed by two dielectric mirrors deposited directly on to fiber ends. A thin air-gap within the cavity is used for wavelength tuning and control by a piezoelectric actuator with positioning resolution of atomic dimensions. The FFP-TF is actuated by a piezoelectric element that changes the pass-band of the FFP-TF by lengthening or shortening the FFP-TF.

In the conventional swept source, FFP-TF usually works at its intrinsic resonant frequency for wide FSR. However, it works at nonresonant frequency in this study. The FFP-TF has the narrow FSR but ultrahigh spectral resolution (narrow instantaneous bandwidth) driven at high frequency far from resonant frequency. This makes the FFP-TF achieve hyperfine tuning. Furthermore, it can work at high tuning speed without the limit of intrinsic resonant frequency. FFP-TF is driven at low voltage range with narrow FSR so that the driving voltage can be linear waveform (the triangular wave) resulting in linear scan. The key to the stable, high-performance characteristics of the FFP-TF is the incorporation of an 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. The FFP-TF (Micro Optics Inc., impedance capacity of $\sim 2.2\,\mu$F, insertion loss of 0.6 dB) acts as a ultra narrowband transmission filter for fine tuning.

Synchronous tuning principle of combined filters is shown in Fig. 3. The combined tunable filters are realized by cascading two filters that play different roles. Polygon filter "coarsely tune" but has wide FSR, while FFP-TF "finely tune" and has narrow FSR. So, the combined filters can realize ultrawide scan range and fairly narrow instantaneous bandwidth simultaneously.

The FSR between two filters muse exhibit a multiple relation as Eq. (1) shows:

$$FSR_{\text{polygon filter}} = n \cdot FSR_{\text{FFP-TF}}, \qquad (1)$$

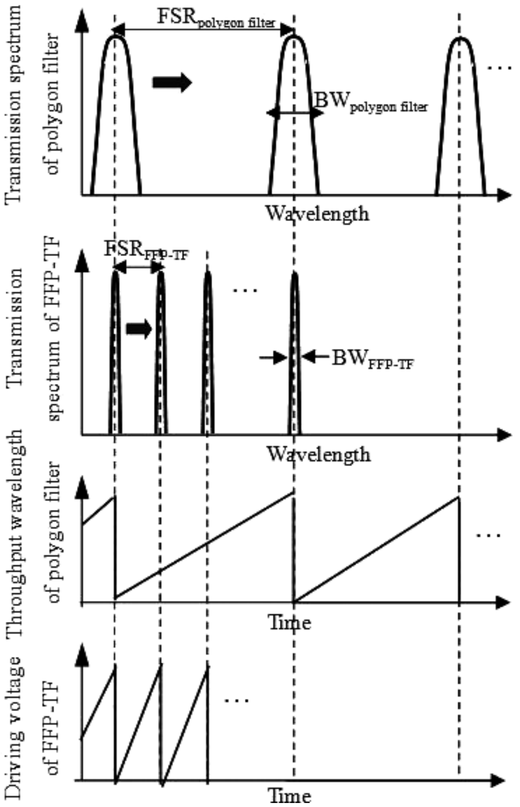

Fig. 3. Schematic diagram of synchronous tuning principle of combined filters. FSR, free spectral range; BW, bandwidth.

where n is an integer. The tuning speed of two filters also has the relation as follows:

$$\nu_{\text{FFP-TF}} = n \cdot \nu_{\text{polygon filter}}. \tag{2}$$

The center wavelength of both filters scan at the same time for high throughput efficiency. The combined filters take advantage of two filters for excellent performance.

3. Experimental Setup

Figure 4 shows the configurable schematic of the FDML laser based on combined filters with parallel SOAs used for this study. The laser consists of ring cavity geometry with two parallel fiber coupled SOAs, a long SMF-28e fiber dispersion managed delay, two polarization controllers, combined filters, two 3 dB fiber couplers, and an output fiber coupler (40:60). The combined filters include circulator, polygon filter, FFP-TF, and waveform driver. The spontaneous emission light from SOAs is filtered by combined tunable filters, and then has the gain in the ring cavity. The amplified laser is output by fiber coupler.

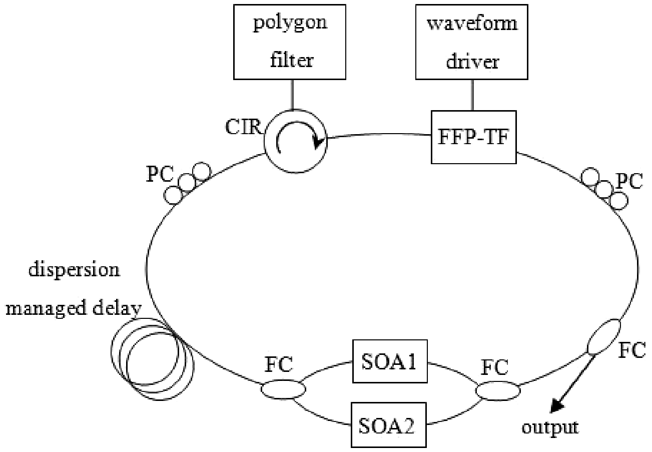

Fig. 4. Schematic diagram of FDML wavelength swept laser based on the combined filters with parallel SOAs. SOA, semiconductor optical amplifier; FC, fiber coupler; PC, polarization controller; CIR, circulator; FFP-TF, fiber Fabry–Perot tunable filter.

In this setup, there are two laser cavities with two SOAs in the parallel manner. SOAs (Inphenix Inc., model number: IPSAD1301, small-signal gain of 22.2 dB) with a gain maximum around 1,300 nm is used as a broadband gain medium. The injection current of both SOAs is 300 mA. Two SOAs with two 3 dB fiber coupler are arranged in parallel in two subcavities using common tunable filters as shown in Fig. 4. The dispersion managed delay is a 13.7 km long SMF-28e fiber with effective refractive index n_{eff} of 1.4677 and loss of 0.35 dB/km. The polarization controllers adjust the state of polarization of laser in ring cavity for higher output power and the other advantageous properties. The fiber circulator couples light from the ring into the polygon filter part and returns it back into the ring, and ensures unidirectional lasing. Waveform driver is a function generator and applies voltage to FFP-TF for filtering. Polygon filter "coarsely tune" with wide tuning range and then FFP-TF "finely tune" with narrow bandpass filtering. Forty percent of the laser is output by the third fiber coupler.

The spontaneous emission spectra of two SOAs are shown in Fig. 5. The wide bandwidth could be obtained by paralleling these SOAs to be suitable for sufficient wide range of the polygon filter's FSR because each SOA generates its own spectrum independently. The FWHM of the SOAs is 69 nm and 67 nm with center wavelength of 1,259 nm and 1,304 nm, respectively. The edge-to-edge range is 145 nm from 1,200 to 1,345 nm and 140 nm from

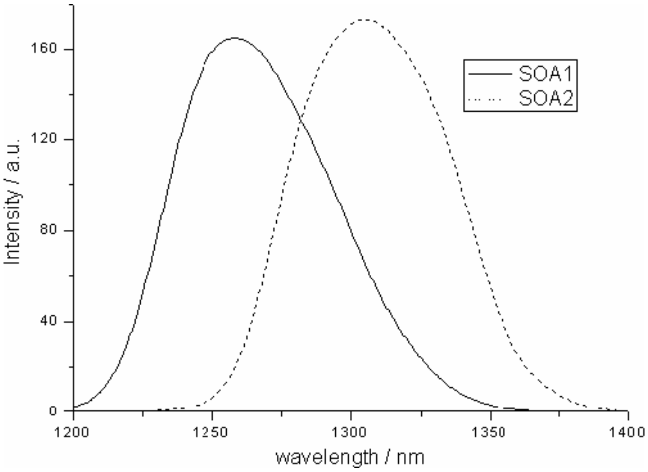

Fig. 5. Spontaneous emission spectra of two SOAs.

1,240 to 1,380 nm, respectively. They have the overlap range of 105 nm from 1,240 to 1,345 nm. By parallel implementation of these two SOAs, it obtains the extension of 40 nm in short wavelength and 35 nm in long wavelength.

The scan speed of the FFP-TF is 180 kHz with FSR of 13 nm. While polygon filter has the FSR of 160 nm and the tunable repetition is 15 kHz, which is the same as the fundamental longitudinal frequency of the total laser cavity. The polygon mirror with 72 facets is rotated at the speed of 208 rounds per second. The fundamental mode is used in our setup avoidance of the loss and potential dispersion effect. To enable FDML operation, a corning SMF28e fiber of 13.7 km in length is incorporated into the laser, and the polygon filter is driven periodically with a period matched to the optical round-trip time of the laser cavity. The proposed Fourier domain mode locking swept laser source provides a tuning range of 160 nm with instantaneous line-width of about 0.01 nm at a sweeping rate of 15 kHz.

4. Conclusions

In conclusion, a detailed analysis on achieving a high bandwidth wavelength, narrow instantaneous line-width, linear swept FDML laser source is presented. The FDML laser is based on novel combined filters with parallel SOAs in ring cavity. The combined tunable filters are realized by cascading two filters which are the polygon filter and FFP-TF. The combined filters can realize ultrawide scan range and fairly narrow instantaneous bandwidth simultaneously. The laser can generate about 15 kHz sweeping rate with a tuning range of 160 nm full width and instantaneous line-width of 0.01 nm. This FDML laser source-based OFDI system is proposed to provide high-quality biological tissue imaging.

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