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ISBN

9780819484260

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Publication Date

2011-02-10

DOI

10.1117/12.875705

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High speed swept source based on polygon-scanner filter and Fox-Smith cavity

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Abstract:

We demonstrate a high-speed and wide-tuning-range swept laser for optical coherence tomography (OCT) imaging. The repetition rate of the laser is twice the speed of the polygon filter and is achieved by using two delay fibers in a Fox-Smith cavity. The performance of the laser is the following: a scanning range of 110nm centered at 1310nm, and the output power of 10mw at a 102.2 kHz sweeping rate.

Keywords: Swept source, Fox-Smith cavity, FDML, OCT

Introduction:

Optical coherence tomography (OCT) is a powerful imaging technology which operates by measuring the magnitude and echo time delay of backscattered light. The applications of Fourier domain OCT systems based on swept source (SS-OCT) have the potential advantages of longer ranging depth and higher imaging speeds[2,3]. SS-OCT systems are important at the 1.3 micron wavelength because no low-cost detector array is available.

A high speed swept source is the key component for SS-OCT systems. Most swept sources utilize an extended ring cavity laser integrated with a fast tunable filter. In a traditional swept source, the light from a semiconductor optical amplifier passes through a fast tunable filter and comes back to the gain medium[4,5]. When the center wavelength of the filter shifts at high frequency, lasing must build up in limited time. This causes the factors, such as increased amplitude noise, low power, broad instantaneous linewidth, which significantly limits the performance of high-speed swept lasers. In 2006, R.Huber introduced a novel swept source, Fourier domain mode-locking (FDML) lasers [6]. When there is a fiber spool in the cavity, the propagating light can pass through the filter synchronously with the optical round-trip time, so the laser works in a quasi-stationary operation. The performance of swept sources can be improved by the FDML technique.

The tunable filter is the key device in swept source. There are two kinds tunable filters: Fabry-Perot scanning filters and polygon-scanner filters. The Fabry-Perot tunable filter is driven by piezos and produces bidirectional wavelength sweeps. The polygon-scanner filter is composed of a polygon mirror for high speed sweeping and a grating for selecting the wavelength. The polygon-scanner filter can generate unidirectional sweeping. For a FDML laser based on a polygon-scanner filter, the scanning rate is limited by the length of the delay fiber and the speed of the filter. Buffered FDML is an efficient way to break the limitation and improve the speed [7]. Buffered FDML needs a filter with a large free spectral range (FSR). For the Fabry-Perot tunable filter, FSR is determined by the gap of the mirrors, it is difficult to get a filter with very large FSR. For the polygon-scanner filter, the factors that influence the FSR of the filter include the grating density, the facets of the polygon mirror, and the center wavelength. It is easy to get a polygon-scanner filter whose FSR is more than 500nm and is thus more suitable for buffered FDML.

The polygon-scanner filter has several schemes. In reference [4, 8], there is a telescope in the filter which is used to focus the dispersion light from the grating on the facet of the polygon mirror. In reference [9, 10, 11], they presented three compact designs without telescope. The filter without telescope is easier to align, has less power loss

from the optics, a shorter cavity length, and smaller footprint that may be beneficial for clinical use.

In this paper, we report a FDML laser based on a Fox-Smith cavity [12]. In a stable continuous wave laser, a Fox-Smith cavity is used to achieve narrow linewidth. In our case, it works as a novel buffered structure. It can increase the repetition rate of the swept source. Compared with other buffered structures, our scheme combines the light in the cavity and has less loss. The laser is centered at 1310nm with a full range of 110nm. The power of the laser is near 10mw at a 102.2 kHz repetition rate.

Experiments

Figure 1 shows the configuration of the swept source with the Fox-Smith cavity. The 50:50 optical coupler is the core device of the Fox-Smith cavity. The left ports have the same structure which consist of the delay fiber and a reflective mirror. The length of delay fiber 1 is 2 km, and the length of delay fiber 2 is half that of fiber 1. The semiconductor optical amplifier (SOA) whose central wavelength is located at 1310nm is the gain medium of the laser (BOA1132, covega). The circulator, SOA, and the filter form the other part of the laser cavity. The laser outputs from the remaining port of the coupler.

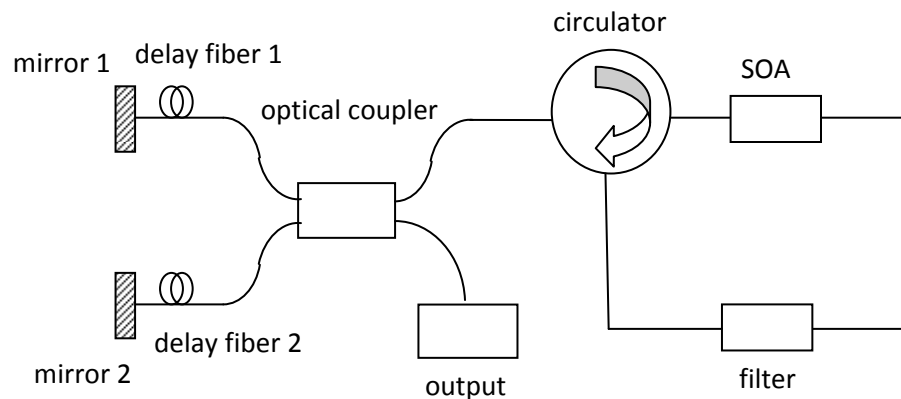


Figure 1, Schematic diagram of the laser, SOA: semiconductor optical amplifier.

The tunable filter is composed of a collimator, a polygon mirror and a grating. The FSR of the filter is determined by the following equation:

$$FSR = 2p\Delta\alpha\cos\theta \quad [1]$$

As the grating works at Littrow condition,

$$2p\sin\theta = \lambda \quad [2]$$

in equation [1] and [2], p , $\Delta\alpha$, λ , θ are the grating pitch, range of the incident angle, center wavelength and the incident angle at the center wavelength.

where $\Delta\alpha = 4\pi/N$, N is the facet number of the polygon mirror.

In our experiment, The grating has a density of 900 lines per millimeter (53-155R, Newport), the polygon (SA34, Lincoln Laser) has 72 facets and the center wavelength is 1310nm, so the FSR of the filter is about 313nm. If the density of the grating is 600 lines per millimeter, The FSR becomes 535nm. From the above calculation, decreasing the density of the gratings is an efficient way for increasing the FSR of the filter. From equation [1], there is another way to increase the FRS by decreasing the facets of the polygon. Compared with the tunable F-P filter, one of the advantages of the polygon-scanner filter is that it is easy to adjust the FSR of the filter. In some cases, such as increasing the duty cycle of the laser, it is necessary to decrease the FSR of the filter. The way to decrease the FSR is also simple, such as using prisms to expand the beam size or using a littman structure.

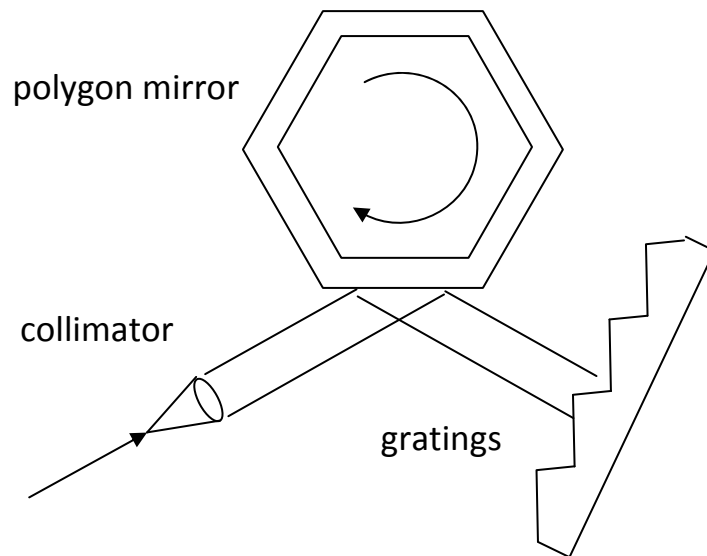


Figure 2, Schematic diagram of the filter

Figure 2 shows the laser output from an oscilloscope. The repetition rate of the pulse is about 102.2kHz, which is double the scanning rate of the polygon due to the fact that the output from different ports have different delay times. The repetition rate of the laser is determined by the length of the delay fiber. The relation is $f = c/2nL$ where f is the repetition rate, c is the speed of light, n is the index of the fiber, and L is the length of the delay fiber. In our experiment, the length of the fiber is 2km, the fiber is SMF-28 from corning, and its index is 1.4677 at 1310nm. The repetition rate from the port with delay fiber 1 and reflective mirror1 is 51.1kHz, the output from the other port is located at the middle of the adjacent pulse because the length of the delay fiber 2 is half of delay fiber 2. As the length of the delay fibers is different, the loss in each port is different. The equal amplitude can be achieved by adjusting the attenuator in delay fiber 2. The duty cycle is about 67%.

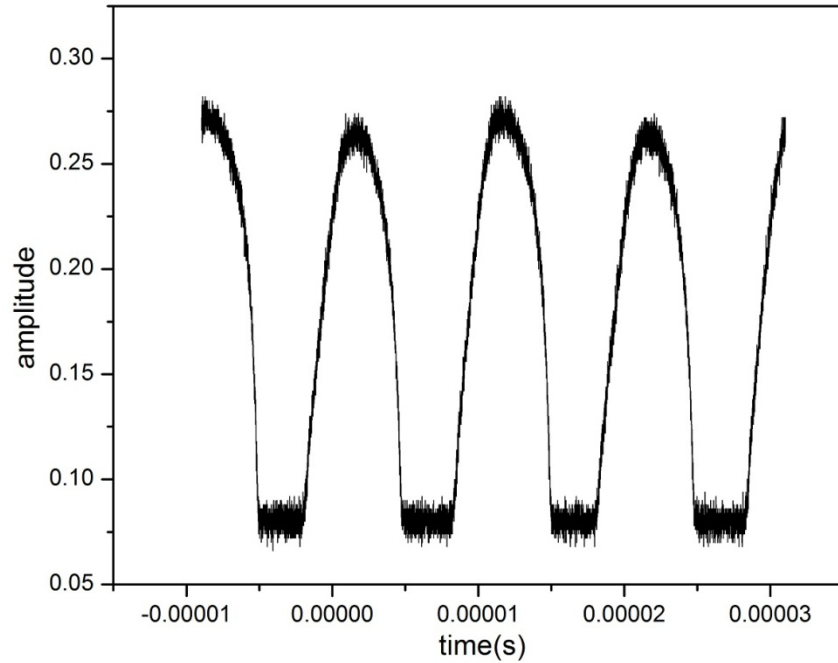


Figure.3 oscilloscope trace of the laser output

Figure 4 shows the laser spectrum measured with an optical spectrum analyzer (AQ6317B, Ando). The center wavelength is located at 1310nm and the tuning range is about 110nm. The calculated FSR is in good agreement with the experimental results ($FSR = \text{wavelength sweep range} / \text{duty cycle}$) as the measured duty cycles is 67%.

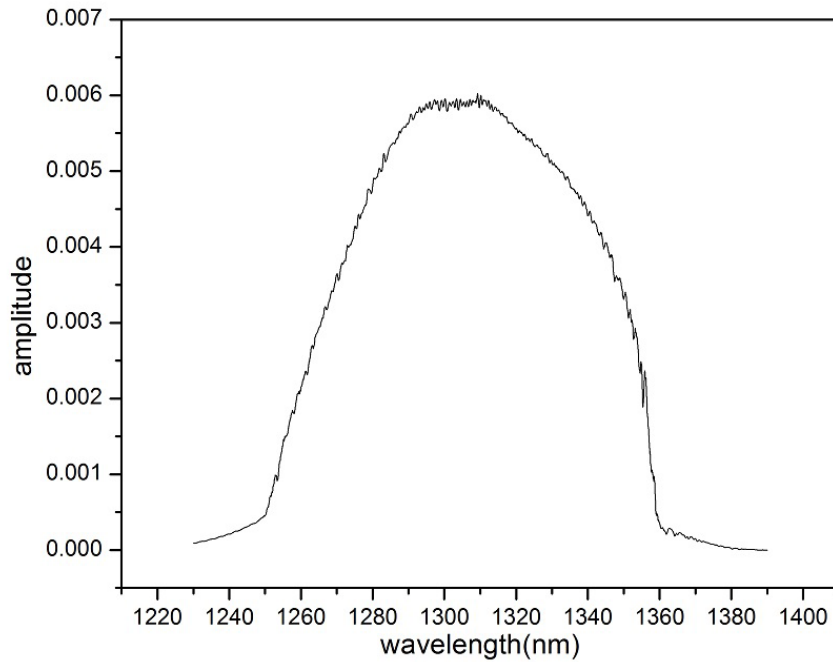


Figure.4 Time-averaged output spectrum

Conclusion

In conclusion, we present a high speed swept source that can be used in swept source OCT system. The laser is based on the polygon-scanner filter which limits the sweep speed. The laser uses a Fox-Smith cavity to double the sweep frequency. In our paper, the output repetition rate of laser is 102.2kHz when the sweep frequency is 51.1kHz. The scanning range is 110nm. The swept source also can be used in other fields, such as sensors system, spectrum system, et al.

Acknowledgments

This work was supported by the National Institutes of Health (EB-00293, EB-10090, RR-01192), Air Force Office of Scientific Research (FA9550-04-0101), Flight Attendant Medical Research Institute (32456), and the Beckman Laser Institute Endowment.

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