Experimental investigation of a frequency swept laser based on erbium-doped fiber for applications in optical coherence tomography

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Abstract

Nowadays, lasers based on erbium-doped fiber play an important role in different applications, such as optical coherence tomography (OCT) systems. An important part of these systems is the light source; in this case we focused on a frequency sweep source. One of the most important advantages of these systems is the possibility of obtaining images with only one sweep. This could be less tedious for the patient and less time consuming. In this work, we present the characterization and implementation of a frequency sweep source based on a ring cavity laser. The cavity used 30 cm of erbium (Er 16^{+}) doped fiber as active medium with a total length of around 7 m. As a result, the maximum measured power was 9.5 mW in continuous wave. A Fabry-Perot filter was used to select the wavelength range, in this paper that range was between 1507 nm and 1584 nm to obtain a bandwidth of 77 nm. We characterizaed the suitable parameters needed to implement this cavity in an OCT system.

Eribum-Doped, Optical Coherence, Frequency Swept, Laser Cavity

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Introduction

The optical coherence tomography (OCT) is recently one of the most demanded techniques in biomedical applications, since it is non-invasive for the patient. OCT is also a noncontact imaging modality that uses a coherent source to obtain high-resolution cross-sectional images of tissue microstructure Fercher et. al. 2003). The 3-D microstructure image volume reveals more morphological information than 2-D images, which is critical in clinical applications such as early-stage cancer detection[2]. The OCT system uses a light source with low coherence and a Michelson interferometer (Drexler & Fujimoto, 2015). The light waves are sent through the biological tissue or other materials and the information is obtained from the interference between the light waves reflected by the tissue and the ones reflected by the mirror of the interferometer. For instance, with this technique, we could scan human tissue with high resolution of micrometers and a penetration depth of milimeters. There are two kinds of light sources that can be implanted in OCT systems, the time domain and Fourier domain. In the literature it is shown that OCT with frequency swept light source in the Fourier domain improve imaging speed over time swept sources. In this work we focused on a frequency swept source, a Fourier domain type. There are two main approaches used to build frequency swept, narrow linewidth light sources: The approach of “post-filtering” uses a broadband light source such as a superluminescent diode or a short pulse laser to generate a broad spectrum, then uses a narrowband tunable band-pass filter with a transmission window narrow enough for the desired instantaneous coherence length (Jianping et. al. 2008).. The approach of post filtering has the advantage that the tuning speed is limited only by the maximum tuning speed of the filter. However, the power of the light source is usually low, due to the high loss of the filtering process.

A complementary approach is “cavity-tuning”, where the spectral filtering element is used inside a laser cavity (Huang et.al. 1991). This last approach is the one used in this cavity, as in this way, we can feedback the cavity and improve the power obtained at the exit. Other frequencies swept sources have been built in different wavelengths range.

In this paper we present a ring cavity design of a frequency swept laser light source as well as its characterizations of power, spectrum and polarization, features that are important for proper use in OCT. We also present the characterization of the amplifier used at the end of the cavity with a gain of around 8 times of the input power. This cavity uses this amplifier to improve the output power going in the OCT for better imaging results. A Fabry-Perot filter is used as band-pass filter, working at 800 Hz. The amplifier also uses EDF as active medium. The porpuse of the cavity presented is to be used in an OCT system for future porpuses on early breast cancer detection.

Experimental Setup

The experimental setup (Figure 1) consists of two parts, 1) erbium-doped fiber ring cavity and 2) the optical amplifier (Ramos-Beltrán, 2013). For the cavity we used a compact laser diode at 980 nm as a pump source (LD1, Compact LD driver by THORLABS, Inc.) which was coupled to the “A” port of a wavelength division multiplexer WDM1, (WDM by AFW, Inc.). The “C” port of the WDM1, which transmits at 1550 nm, was coupled to a 30 cm of erbium-doped fiber $Er^{+}16$ (EDF1). In order to block the pump signal at 980 nm, the EDF1 was connected to the WDM2 (by AFW, Inc.). Afterwards, it is connected to an optical circulator (by AFW, Inc.) to prevent that the signal travels in the opposite direction.

The circulator is connected to a Fabry-Perot filter (FFP-TF2, Micron Optics, Inc.), which acts as a transmission filter to selecting the wavelength emission of the laser, the output of the Fabry-Perot goes to a coupler (optical coupler-90/10-0-N by AFW, Inc.) with a ratio of 90/10. The 10% of the signal is used as the feedback of the cavity while the 90% was used to measure the power and the spectrum of the output signal and also it is coupled to the amplifier (Figure 1).

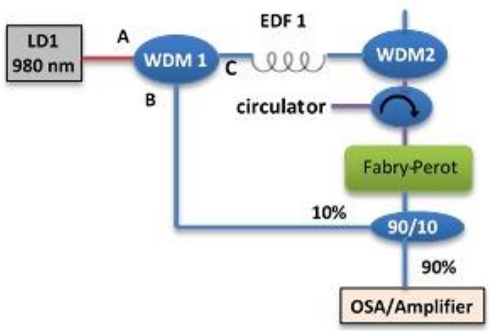


Figure 1. Experimental setup for hering cavity.

In figure 2 we show the experimental setup of the optical amplifier. The output of the cavity is connected to a circulator that goes to the "E" port of a WDM3 (by AFW, Inc.). The "D" port of the WDM3 receives the signal from a second compact laser diode (LD2) and the "F" port is connected to the EDF2 followed by the polarization controllers (PC, by THORLABS, Inc.) to maintain the polarization constant at the output of the system.

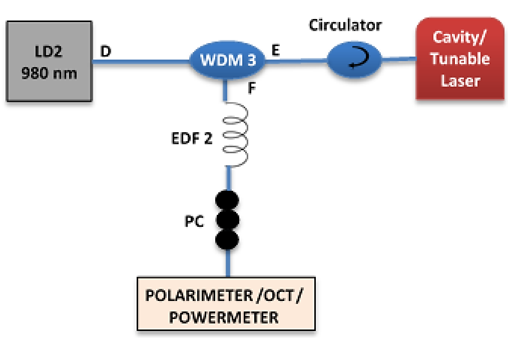
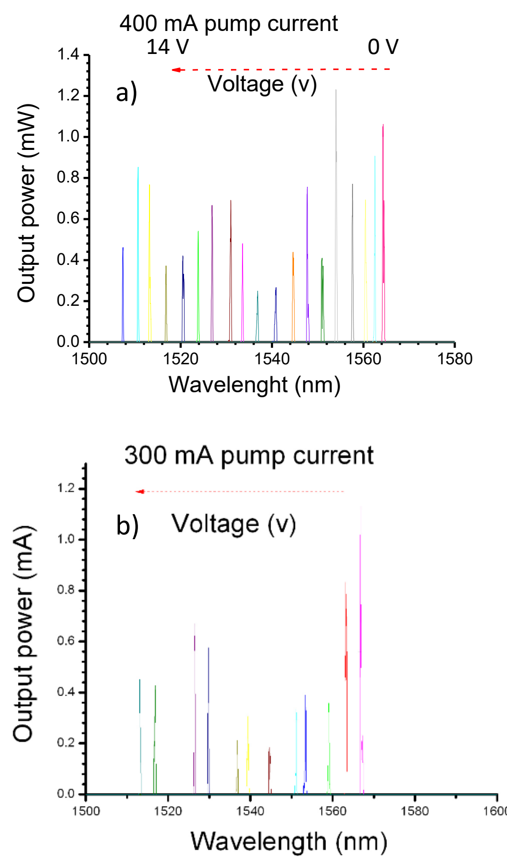


Figure 2. Experimental setup of the amplifier.

Experimental methodology

Here the cavity was characterizaed in terms of the spectrum changes due to variations in either the pump current or the voltage of the Fabry-Perot. Results obtained are shown in Graphic 1. Moreover, in order to obtain these spectra, the output of the cavity was connected to an OSA (Optical spectrometry instrument by SienceTech, Inc.) and the voltage was varied from 0 V to 14 V. Once the first peak of the spectrum appeared in the OSA we started to increment the voltage in 0.2 V intervals and its corresponding spectrum was recorded.

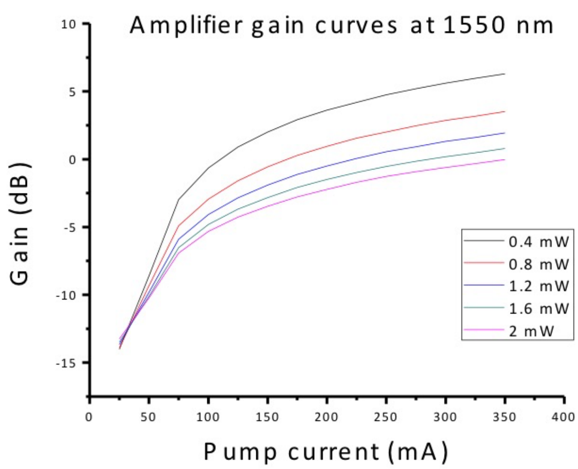


Graphic 1. Characterization of the spectrum at the end of the cavity for different voltage applied at the Fabry-Perot filter; a) LD1 at 400 mA; b) LD1 at 300 mA.

Now, in order to carachterize the amplifier, we used a tunable laser. Firstly the output power of the amplifier was registered as we increased the tunable laser input power from 0.4 to 2 mW. Afterwards as we know the output (P_o) and the input (P_i) power the amplifier gain (Graphic 2) can be computed by using the following equation:

$$G = 10\log\left(\frac{P_o}{P_i}\right) \qquad (1)$$

The polarization of the signal of the amplifier was characterized by using a polarimeter for different pump currents from LD2 and different input powers of the tunabla laser. The maximum gain was about 7 dB. Moreover, amplifier gain curves are shown in Graphic 2, where can be observed that the saturation power is beyond the maximun pump current of LD1 at 400 mA and that the signal is amplified almost 8 times.

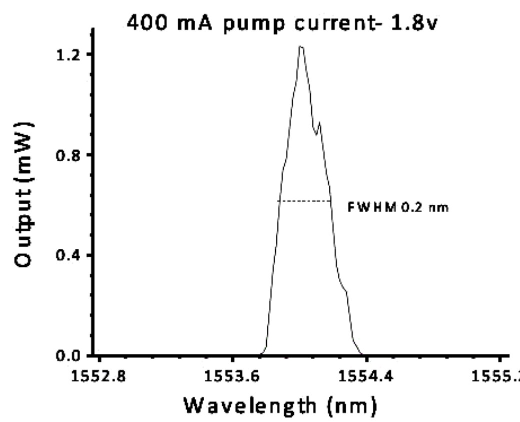


Graphic 2. Gain curves for the amplifier for different pump currents.

Once these steps were performed the the whole setup output as a function of the input power, the Fabry-Perot wavelength and the polarization were experimentally characterized.

Results

The laser emission after the cavity was measured with a power meter and it reached a peak of 1.2 mW at 400 mA input. After the amplifier, the maximum power obtained was 9.5 mW, nine times the signal of the cavity without the amplifier. The total spectrum obtained from the Fabry-Perot filter for all the different pumping powers moved between 1507 and 1584 nm, which respresents a total bandwidth of 77 nm. In Graphic 3 it is shown a single peak spectrum with a full width at half maximum (FWHM) of 0.2 nm.



Graphic 3 Single peak spectrum with a FWHM of 0.2 nm.

From the characterization procedure, it was observed that the wavelengths were shifted to the left as the voltage increased as described in Graphic 4. The wavelength shift versus the applied voltage has a linear relationships which do not change in a senstive way if the current is varied. For instance we get an slope of -22 for 100 mA, 200 mA, and 300 mA and of -16.5 for 400 mA.

Another important issue that requires to be characterized is the bandwidth of each output spectrum. As can be seen in Graphic 5, the bandwidths were not much different among pump powers. The widest one was 77 nm for 200 mA and the narrowest one was 53 nm at 300 mA.

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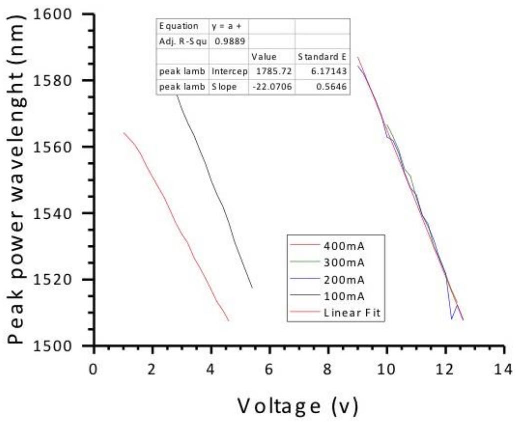
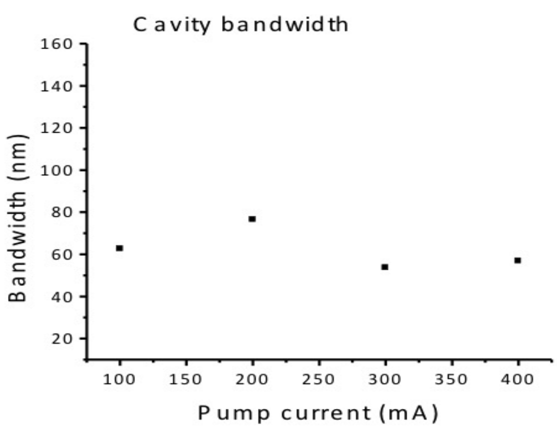
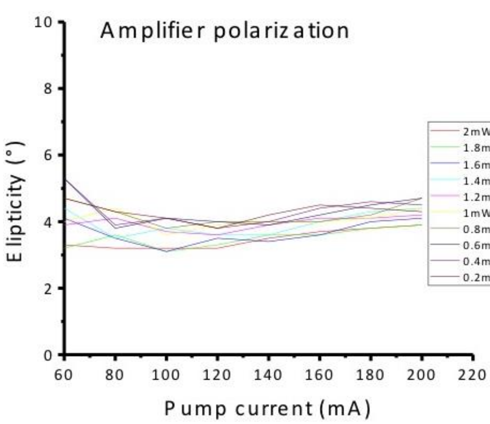


Graphic 4. Shows how the wavelegnths shift down when increasing the voltage of the Fabry-Perot filter.

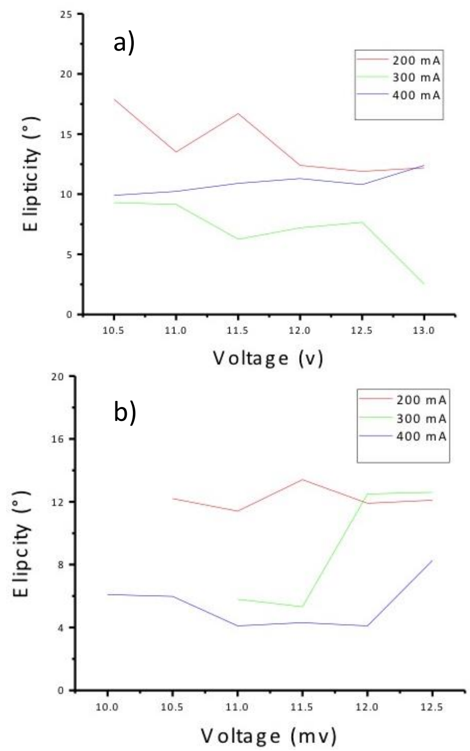


Graphic 5. Bandwidth of the whole spectrum for different pump currents.



Graphic 6. Polarization at the output of the amplifier alone.

In the Graphic 6 the behavior of the polarization of the amplifier alone it is shown. Here can be noted that it remains constant for pump currents higher tan 80 mA and that it fluctuates for different input powers only by 1.5 degrees. Moreover, the polarization characterizaton of the overall experimental setup (cavity plus the amplifer) it is showed in Graphics 7, were can be appreciated that the elipticity remains constant for the maximun current power of 400 mA, also remains constant when the voltage applied to the FPI within the range from 11.5 to 12.5 V at 300 mA.



Graphic 7. Elipticity changes as a function of the applied voltage to the Fabry-Perot filter in a a) decreasing way and b) increasing way.

In Graphic 8, it is shown that the maximum power obtained is 9.5 mW and 3.7 mW for 300 and 400 mA respectively. These are the power levels in which we are interested since these are the current where the polarization remains constant.

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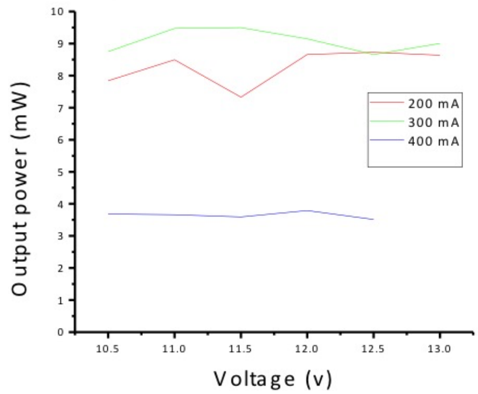
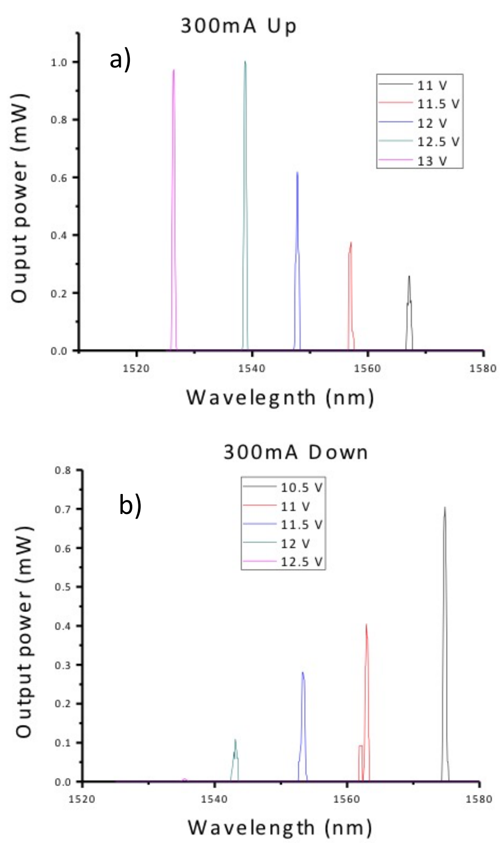


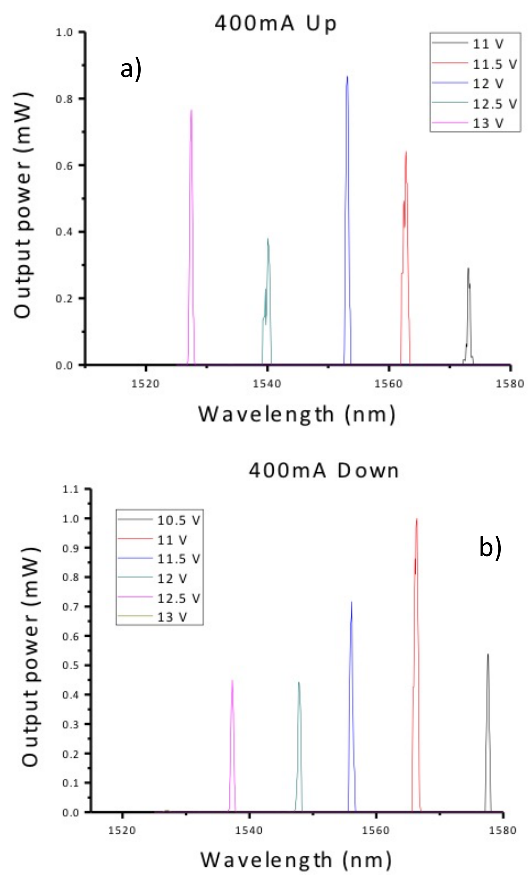
Graphic 8. Output power as the voltage applied to the Fabry-Perot filter is increased.

Moreover, spectra at the end of system formed by the cavity and the amplifier for 300 mA and 400 mA are shown in Graphic 9 and 10 respectively. Here the voltage was varied in both directions (increasing and decreasing the voltage).



Graphic 9. Behaviour of the cavity and amplifier spectrum pumped with 300 mA and as the voltage is a) increasing and b) decreasing.

It is important to point out that the power levels showed in these graphics is approximatly 40% of the total power since it is connected to the 40% part of the 40/60 coupler used. Additionally, from these graphics it can be seen that spectra for increasing the voltage and decreasing it are mirrors of each other, wich tell us that the filter works in the same way for both directions. Hence, the output peak are shifted down in wavelength as the voltage is increased and it has the same behavior before reach the amplifier (Graphic 11).



Graphic 10. Behaviour of the cavity and amplifier spectrum pumped with 400 mA and as the voltage is a) increasing and b) decreasing.

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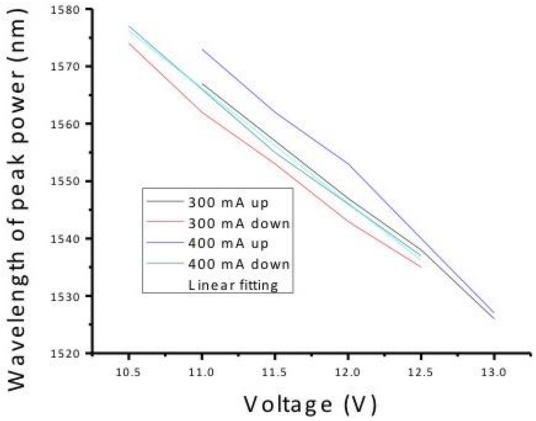

Graphic 11. Wavelength shift down when the voltage of the Fabry-Perot filter increases, for the cavity and the amplifier.

Conclusions

A frequency swept laser cavity based on erbium-doped fiber with a bandwidth of 77 nm at 200 mA was implemented. The maximum power obtained was 1.2 mW with a driver current of 400 mA. The bandwidht of each peak emission on continuos wave was about 0.2 nm. A characterization of the Fabry-Perot filter that is inside of the cavity was performed. An amplifer also based on erbium doped fiber was implemented, whose maximun output power was 9.5 mW. The elipticity of the output signal fluctuates, in the best case, from around 3.5 to 5 degrees before the amplifier. After the amplifier elipcticy remains constant for pump current of 400 mA and a voltages from 10.5 v to 12.5 v which is adequate for the OCT system. Finally, we achieved a spectral swept power source that can be used in an OCT system for a possible application in the early detection of breast cancer.

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