Towards a Fourier-Domain mode-locked laser system with an integrated Mach-Zehnder interferometer as frequency filter

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The use of an InP based integrated asymmetric Mach-Zehnder interferometer (AMZI) in a Fourier Domain Mode-Locked fiber-based laser for optical coherence tomography (OCT) application is discussed and characterization results are shown. The need for high-speed scanning source is crucial for OCT images, since it helps to avoid blurriness and artifacts due to the motion of biological tissue during in-vivo measurements. In this work, we observed that replacing the commonly used piezo-driven Fabry-Perot filters (FFP) with monolithically integrated ones, enables a laser system with higher tuning speed and consequentially reduced cavity length. The laser consists of a fiber ring cavity containing a semiconductor optical amplifier and the integrated AMZI. The laser wavelength is tuned at the cavity roundtrip frequency by applying reverse bias voltage on an electro refractive modulator present in one of the arms of the integrated AMZI. A preliminary characterization reveals a 3 nm comb width around 1530 nm, together with 83.3 ns output pulses for a 16 m fiber-based laser with a 12 MHz repetition rate.

Keywords: InP, Semiconductor Lasers, Fourier-Domain Mode-Locked laser

Introduction

Fourier domain mode-locked (FDML) lasers are among the fastest wavelength-swept light sources. They are used in many applications, like optical coherence tomography (OCT) [1] and Raman or two photon microscopy [2]. FDML lasers consist of long ring fiber cavities with tunable Fabry-Perot bandpass filters (FFPs). The transmission wavelength of the mechanically tunable FFPs is modulated sinusoidally with a repetition period equal to the fundamental cavity round trip time. In this way, these lasers overcome the limitation of the buildup time of the laser signals from spontaneous emissions, allowing for fast sweeps up to 290 kHz [3]. The slow scans of FFPs are currently limiting the tuning speed and the dimensions of the laser cavities. New approaches introduced lithium-niobate Mach-Zehnder interferometers [4] as wavelength-tunable comb filters in such FDML fiber ring lasers. In this work we show preliminary data on an integrated AMZI bandpass tunable filter with reversely bias driven InP based phase modulators in a fiber based FDML laser. The phase modulators allow for faster scanning of the AMZI as well as using other time dependencies of the maximum transmission wavelength as a function of time than sinusoidal. The AMZI characteristics and the laser schematics are reported. Optical and electrical spectra, and output pulse duration obtained from the FDML. These results can be considered as a milestone for the monolithic integration of FDML laser on InP, to achieve GHz scan speeds~~,~~ as theoretically modeled [5], [6]. Moreover, the use of an InP based integrated AMZI, increases the possibility of using different driving voltage waveforms, which leads to different power distributions over the modes of the generated frequency combs.

Laser Design and DC operation

The fiber-based laser design, with schematics in Fig. 1 (a), consists of ring cavity with the AMZI as a tunable bandpass filter. The gain medium is a discrete component semiconductor optical amplifier (SOA), where its substrate temperature is stabilized to 20° trough Peltier and water cooling. Two optical isolators are included inside the ring cavity to ensure only counterclockwise (CCW) propagation of the light. The output of the AMZI is connected to 2x2 output coupler where 90% of the optical power is fed back to the laser cavity and 10% is extracted as the output signal. A Single Mode fiber (SMF) delay line leads to a total cavity length of 16.071 m which corresponds to a cavity FSR of around 12.038 MHz calculated as:

$$FSR_{cavity} = \frac{c}{n_{g1}L_{AMZI}+n_{g2}(L_{total}-L_{AMZI})} \tag{1}$$

Where n_{g1}=3.66 is the group index of InP waveguides at 1550 nm, n_{g2}=1.55 is the group index of SMF and $L_{AMZI} = 4.6\,mm$ is the optical path length on the InP chip. The free spectral range (FSR) of 6 nm of the AMZI is determined by the geometrical length mismatch ΔL (97 µm) between the two arms. The wavelength tuning of the laser is done by applying a reverse bias voltage to one of the phase modulators of the AMZI , with a linear phase change of 15°/V.mm [7]. It is important to mention that to achieve FD-MLL operation in the proposed design, it is essential that the modulation is applied only on one arm of the AMZI to exploit both the effects of wavelength filtering and phase modulation. In this way it is possible to obtain a fixed phase relation between adjacent modes.

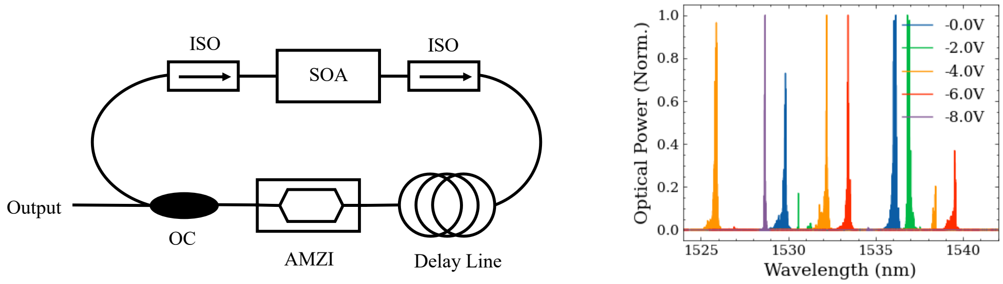

Fig.1 (a) Schematics of the fiber-based Fourier Domain Mode-locked laser investigated in this work. (b) Laser spectra for different DC bias conditions applied to the AMZI.

The laser threshold current is 200 mA, and the optical power measured on the photodetector is 110 μW at 320 mA. The optical power is mainly hampered by the coupling loss between InP chip and the fiber, and it has been measured at the output of the AMZI where the highest cavity loss occurs. The laser tuning is investigated applying reverse bias voltage to the filter between 0 V and -7 V with 1 V step. In Fig. 1 (b) is possible to observe different spectra as function of the reverse bias voltage measured with a resolution of 20 MHz (APEX 2641-B). From the plots, we can observe three spectral mode groups with 6 nm spacing corresponding to different AMZI transmission periods. From the wavelength tuning we observe that lasing modes are hopping between the different filter maxima. This is since the lasing wavelength occurs where the minimum loss is present and small variations in loss for the different maxima occur during tuning. This behavior is a limitation to the FDML operation, since the laser hopping between different wavelengths will occur then as well.

Fourier Domain Mode-Locking Operation

The mode-locking operation of the laser is investigated tuning the AMZI filter with a sinusoidal drive signal with the same frequency as the FSR of the ring laser cavity. Electrical spectra from a 12.5 GHz photodetector, monitoring the laser output are recorded to investigate the mode-locking operation with respect to the modulation frequency of the AMZI tunable filter. The optimal frequency was found to be 11.975 MHz, for an SOA current of 318 mA. The blue curve in Fig 2 (a) shows the electrical spectrum when the modulation of 11.975 MHz is applied to the AMZI. RF power at the cavity repetition rate is measured to be -15.7 dBm, which is 85 dB higher than the noise floor (-100 dB). This is used as a clear indication of mode-locking operation of the laser. As we detune the modulation frequency by 10% we observe (red curve in Fig 2 (b)) the presence of beating frequencies between the laser fundemental frequency and the modulation frequency. A high-resolution scan of the modulation frequency is made to observe the effect of smaller detuning on the RF power. We see that a detune of 5 KHz, 15 KHz and 60 KHz results in 1 dB, 3 dB and 5 dB of RF power drop respectively. In the same way, a detuning of ±5 KHz results in a 3-4 dB drop of the optical spectral power. Fig. 2 (b), shows the optical spectrum of this FDML laser measured at 20 MHz resolution for different AMZI modulation depths (V_{pp}). It is clear how the optical power is concentrated at the edges of the frequency comb generated by the filter sweep. This is a characteristic result for a sinusoidal drive signal applied to the AMZI filter as we predicted from optical simulations [6]. The asymmetric shape of the comb with respect to the center can be explained with the residual absorption of phase modulators as function of the reverse bias voltage [8]. The effect of the modulation depth is observed by the increase in the comb width and a simultaneous decrease in the average power. This happens since the larger the modulation depth, the shorter the fraction of time the laser is operating at one of the cavity modes, as theoretically explained in [6].

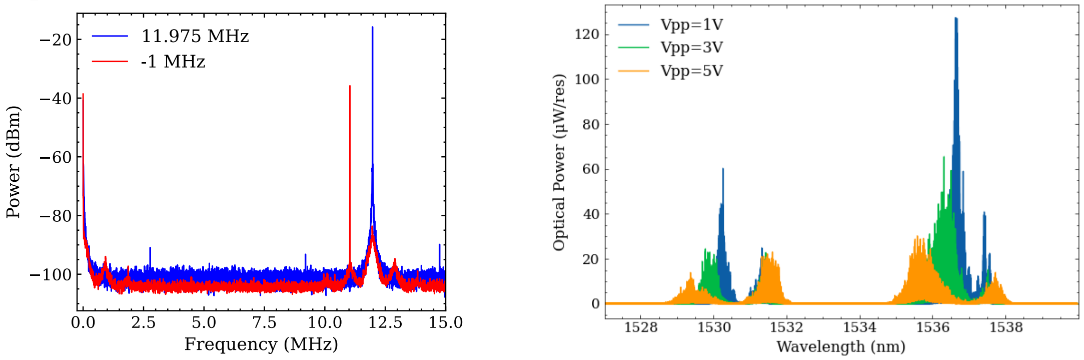

Fig. 2 (a) Electrical spectrum for FD-ML operation at the fundamental frequency (F_{Mod}=11.975 MHz) and for 1 MHz detuning. b) Optical spectra for different V_{PP} applied to the AMZI

The output pulses, after passing through an Erbium doped fiber amplifier (EDFA) are recored with a 12.5 GHz bandwidth photodiode and studied to identify the FDML operation. The RF signal applied to the AMZI filter is used to trigger the osciliscope acquisition and the time traces were averaged over 600 sweeps. The obtained output pulses, shown in Fig. 3 (a) reveal how the output power is distributed over the whole pulse period of 83.3 ns (11.975 MHz repetition rate). This can be interpreted as a second indication for FDML operation. The presence ofdrops in output power occuring at the maximum drive voltage of -5V may be due to the fact that the laser is operating outside of the gain window of the EDFA. This happens due to mode-hopping between different maxima of the periodic filter function as shown for DC laser operation in Fig. 1 (b). To evaluate the phase relation between different spectral modes in the obtained combs, the output comb is spectrally filtered over different modes to determine the relative time delay of different spectral components. During the wavelength sweep of

FD-MLL, we expect the existence of two pulses at a specific filtered wavelength within the sweep range of the laser. The time delay between the two pulses δt can be linked to the filtered wavelength λ_{filter} by: $\delta t = \frac{\lambda_0 - \lambda_{filter}}{\lambda_1 - \lambda_0} . T_{period}$ where $\lambda_0 = 1528.3\, nm$ and $\lambda_1 = 1531.40\, nm$ corresponds to the wavelengths at the edge of the sweep range of the obtained frequency and T_{period} is the round trip time. Fig. 3 (b) shows 500 ns output time trace corresponding to filtered output spectrum at 1530.40 nm. We observe the existence of two pulses in the round-trip time of 83.3 ns and the time delay between them is found to be 56 ns which is the delay between the two pulses at 1531.40 nm.

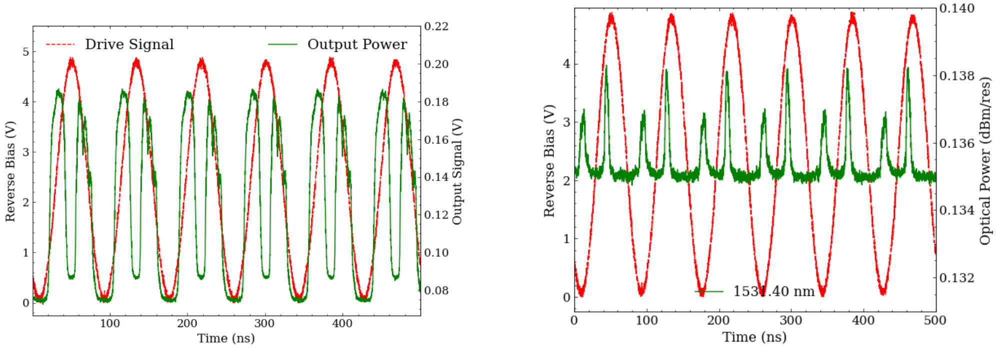

Fig.3 (a) 500 ns recoreded signal time traces (green) overlapped with the drive signal applied to the AMZI.(red) (b) 500 ns recored signal time traces for sinusoidal same driving and a filtered spectrum at 1530.4 nm (I_{SOA}=318 mA, $F_{Modulation}$ =11.975 MHz, V_{PP}=5, V_{Offset}=-2.5 V, G_{EDFA}=11 dB)

Conclusions

This first results on the use of an integrated AMZI as a fast tunable filter in FDML laser are here presented. A 3 nm frequency comb together with 83 ns long pulses have been experimentally observed. This work is intended to be a first step into the realization of a fully integrated FDML laser with GHz scan rates to be used as a source for OCT endoscopy and imaging.

Acknowledgments

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