Ph. D. project: Novel concepts for improving Swept Sources for Optical Coherence Tomography

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I. INTRODUCTION

Optical Coherence Tomography (OCT) is an emerging technique that allows to record non-invasively volumetric images of scattering materials with depth resolutions down to a few microns, which is roughly the size of bigger cells. It is nowadays mainly used for medical applications and of special interest for ophthalmology, dermatology and endoscopy[1].

One distinguishes between different OCT schemes, the "classic" Time Domain(TD)-OCT and the newer Frequency Domain(FD)-OCT. FD-OCT has the advantage that each depth scan is obtained in one instant by Fourier-transforming the spectral response of the sample, thereby speeding up the image acquisition as well as reducing the amount of moving parts in the setup. The sample spectrum can be recorded by using a broadband light source and a spectrometer. This method is called Spectral Domain(SD)-OCT. Alternatively, one can use a single photo diode and a tunable narrowband light source. In order to achieve adequate data acquisition speed, the output wavelength has to be swept rapidly over the tuning range, which leads to the term Swept Source(SS)-OCT.

The choice of the operating wavelength is an important matter, depending on the target application. While it is easier to achieve high depth resolutions at lower wavelengths, scattering becomes in general lower for light of higher wavelengths which makes higher penetration depths in turbid media possible. Typical wavelength ranges for medical OCT are located between 600 nm and 1300 nm[1]. The intermediate range around 1060 nm has been found interesting, because water, being a major constituent of biologic tissue, has here a minimum in absorption as well as in dispersion. This is beneficial especially for imaging the retina and the choroid[2], where the probing light has to pass the vitreous and should preferably be attenuated and dispersed as little as possible.

While SD-OCT is well-established in the visible range, fast high-resolution line cameras for the near-infra red range are up to now difficult to find. Therefore, SS-OCT is more common for the latter wavelengths. It has also the advantage that balanced detection is possible, which eliminates certain noise sources and enhances sensitivity[3].

II. PROJECT DESCRIPTION

The objective of this Ph. D. project is to set up one or several swept sources working at the wavelength range around 1060 nm and to investigate a number of concepts for improved performance. In the later stages of the project these will be brought to application. The source will be an external cavity laser employing one or more Semiconductor Optical Amplifiers (SOA) as gain medium and a rapidly tunable narrowband filter that selects the wavelengths to be fed back to the gain medium. As one approach, the entire source will be set up in fibre optics, as shown in Figure 1, which keeps the handling simple and ensures high stability. In this case, a so-called Fiber Fabry-Perot Tunable Filter will be used, that features high possible finesse values, while being compact, very flexible and free of alignment. Additionally, it will be investigated, whether a setup in free-space optics can help to circumvent the inherent difficulties of fibre optics, and which solution is of advantage dependent on the application. Several new concepts will be implemented in order to improve certain characteristics of the light source which are important for the overall performance of the OCT system.

A. Gain-multiplexing

The spectral bandwidth—for a swept source this corresponds to the sweep range—should be as high as possible, because the depth resolution improves with increasing bandwidth. State-of-the-art SOAs for 1060 nm have gain

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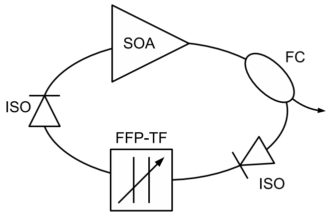

FIG. 1: Schematic of the basic swept source setup in a fibre optic implementation. SOA: semiconductor optical amplifier, FFP-TF: Fiber Fabry-Perot tunable filter, FC: fibre coupler, ISO: optical isolator

bandwidths of 70 to 80 nm that lead to a depth resolution of little less than 10 μm in biologic tissue. In order to resolve even smaller details, the light source sweep range shall be extended beyond 100 nm by employing several SOAs with shifted gain spectra.

In preliminary experiments it could be shown that using two SOAs in series as gain medium can bring a significant improvement in bandwidth, compared to the traditional configuration with one SOA as gain medium and one as booster. Figure 2 shows schematically the two light source configurations under comparison and the corresponding maximum bandwidths for different filter sweep rates.

But the most suitable approach to increase the bandwidth is probably to use several gain media in parallel. This has been demonstrated at 1300 nm with two SOAs, simply by splitting the light into two branches with fiber couplers[4]. If more than two SOAs are used, though, a suitable wavelength-multiplexing technique is needed for distributing and re-combining the light, so that cavity losses are kept low and interference noise is avoided. It will be investigated, whether this can be achieved with an active device, like a high-speed electro-optic switch, or a passive component, e. g. a dichroic mirror or edge filter with a very steep transition at an appropriately chosen threshold wavelength λ_{thr}, like illustrated in Figure 3.

B. Increased output power

Sufficiently high output power is necessary for a good signal-to-noise ratio and a high penetration depth. Therefore, one wants to operate close to the maximum allowed level of illumination. Up to now, a single SOA—especially at 1060 nm—could not deliver the desired power, so that usually booster amplifiers were added which introduce additional excess noise[5, 6]. Recently developed SOA technologies with higher saturation power will be tested for their feasibility in a swept source. Besides the “classic” narrow-stripe devices, Tapered Amplifiers, which deliver high output power due to their special architecture, seem promising for a swept source that does not require a booster[7]. The integration of a Tapered Amplifier into a fibre-based setup is challenging, though, because the output beam is highly astigmatic, and fibre-coupled devices are not yet commercially available. Alternatively to a partially fibre-based system, a Tapered Amplifier could be integrated into an all-free-space resonator. Possible examples are a ring cavity with a micro-electro-mechanical Fabry-Perot filter, or a short linear cavity with a grating-based filter at the narrow facet of the amplifier.

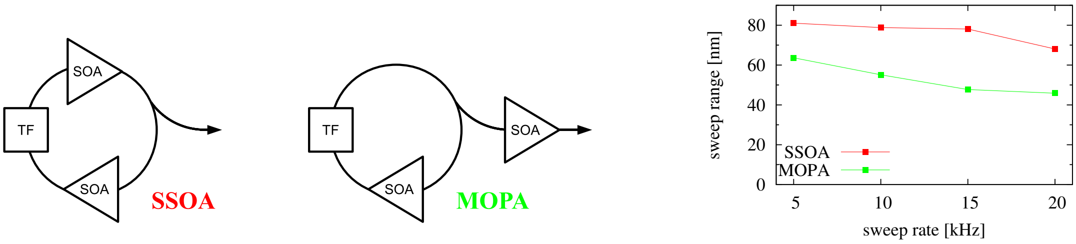

FIG. 2: Gain-multiplexing with serial SOAs. left: Simplified schematics of the configurations under comparison, *Serial SOA* (SSOA) and *Master Oscillator/Power Amplifier* (MOPA); right: Maximum bandwidth for different sweep rates.

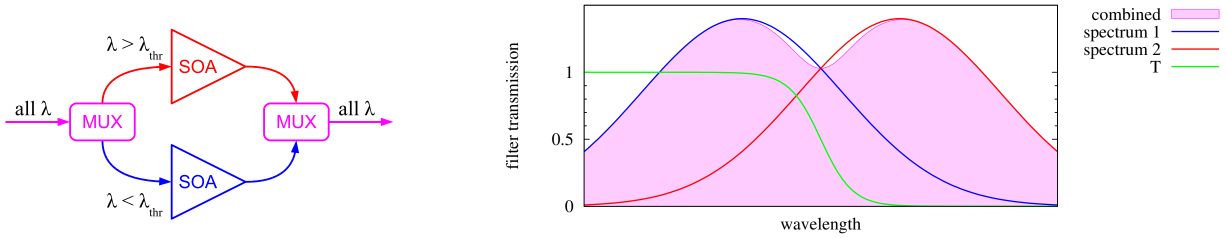

FIG. 3: Gain-multiplexing with parallel SOAs. left: schematic setup with two SOAs; right: example of two offset gain spectra and resulting combined spectrum for given edge filter characteristics (spectrum 1 weighted with $T(\lambda)$, spectrum 2 weighted with $1 - T(\lambda)$).

C. Fourier Domain Mode Locking

In order to record two- or three-dimensional datasets without motion artefacts (which are hardly avoidable in in-vivo measurements), the depth scans have to be performed at a high repetition rate, which corresponds to the sweep rate of the light source. When the filter sweep rate is increased beyond a certain threshold—usually on the order of several ten kHz—the overall performance degrades, because light of each wavelength does not have enough time to build up laser radiation from ASE while it can pass through the filter[5]. In order to overcome this limitation, one can synchronize the filter sweep rate with the cavity round trip frequency, which requires requires a delay line, typically several kilometres long. The light can thus circulate continuously in the resonator without interruption. This technique, called Fourier Domain Mode Locking (FDML), can easily be realized at 1300 nm, because the zero-dispersion wavelength of standard silica fibre is located in this range and the round trip frequency does not vary too much for the different spectral components[8]. At 1060 nm though, dispersion in standard fibre limits the effective bandwidth of the light source and a method for compensation has to be developed[9]. Possible solutions, that will be investigated within this project, could be based on dispersion-tailored special fibres or chirped Fibre Bragg Gratings.

Initial experiments using a dispersion-shifted Photonic Crystal Fibre (PCF) for the delay line have recently been performed in collaboration with the group of Robert Huber at the Ludwig-Maximilans-Universität in Munich, Germany. The PCF, originally tailored for supercontinuum generation, has its point of zero-dispersion at 1040 nm, and is therefore a promising candidate this application. But due to high insertion loss, laser operation is hardly possible at all. It will be investigated, whether this loss is inherent or if it can be reduced. Further experiments are planned to determine, whether the PCF approach is in principle feasible for FDML.

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