A fully akinetic FDML-like swept source for SS-OCT

Rene Riha[a] and Adrian Podoleanu[b]

[a,b]Applied Optics Group, University of Kent, School of Physical Sciences, Canterbury, Kent, CT2 7NH, UK

ABSTRACT

In this summary, a new, fully akinetic FDML-like or so-called dual resonance sweeping regime for swept source optical coherence tomography, SS-OCT, at 1060 nm is demonstrated. A chirped fiber Bragg grating is used to provide sufficient dispersion in the laser cavity and a fiber intensity modulator is employed to modulate the optical field in the fiber cavity. A tuning range of 40 nm for sweep frequency of ≈ 1.7 MHz is obtained. Similarities in the operation of the dual resonance regime with a conventional dispersion tuned swept source and the FDML concept are included.

1. INTRODUCTION

Optical coherence tomography (OCT) is a non-invasive, non-contact imaging technique based on low-coherence interferometry.[1] The essential parameters determining the OCT performance are the axial resolution, imaging range and speed as well as the sensitivity drop-off with imaging depth. One of the OCT methods that in the last decade has proven MHz sweep rates is the swept source optical coherence tomography (SS)-OCT.[2]

Several principles of tuning fast the wavelength have been demonstrated. Some of these concepts are based on mechanical actuation of spectral filters, such as Fabry-Perot tunable filters,[3] polygon mirror scanners[4] or tunable micro-electromechanical systems (MEMS).[5] Dispersion tuned akinetic swept source (AKSS) based on active mode-locking in dispersive fiber lasers have also been reported.[6]

We here report a dispersion tuned AKSS operating in the dual resonance sweeping regime at 1060 nm. A fiber intensity modulator as a mode-locking element is used in a similar configuration reported for the dual resonance regime at 1550 nm.[7] Using the intensity modulator as a separate mode-locking element has been shown to possess better wavelength tuning properties than modulating the driving current of a gain medium to mode-lock the optical field in the cavity.[8] By employing the dual resonance regime, sweep frequencies over 1 MHz could be achieved in long length cavities, where otherwise conventional dispersion tuned AKSS configurations would allow only a few kHz sweeping rate.

2. METHODS AND SETUP

The dispersion tuned AKSS being currently researched for the dual resonance sweeping regime at 1060 nm is shown in Fig. 1. The source consists of four three elements (optical parts) essential for dispersion wavelength tuning: semiconductor optical amplifier (SOA) as a gain medium, a fiber Mach-Zehnder intensity modulator (IM) as a mode-locking element and a chirped fiber Bragg Grating (cFBG) as a chromatic dispersive element. Optical circulator (CIRC) conveys the optical field to the cFBG and optical isolator (ISO) prevents bi-directional lasing in the cavity. To maximize transmission in the cavity and reduce polarization spectral modulation, inline polarization controller (PC) is used between the PM fiber loop (violet color) and non-PM cFBG (orange color). The total cavity round trip length $L \approx 117$ m determines a resonant frequency of $\overline{f}_r \doteq 1.7$ MHz.

A schematic diagram of the signal generator driving the IM is detailed in Fig. 1 as well (inside the green dashed area). A voltage-controlled oscillator, VCO, is driven by a ramp function from an arbitrary function signal generator, AFSG. The VCO output signal is directed to an RF pulse signal generator, PG, with a constant pulse width of 50 ps and a repetition frequency f_m given by the frequency of the sinusoidal signal from the VCO. The pulsed signal modulation technique has been proven to possess better modulation and wavelength filtering properties in comparison with sinusoidal modulation.[6] Finally, the pulses are amplified by a radio frequency amplifier, RFA, and then applied to the IM.

To mode-lock the optical field in the cavity, the modulation frequency f_m must match an integer number m of the fundamental resonant frequency f_r:

$$f_m(\lambda) = m f_r(\lambda). \tag{1}$$

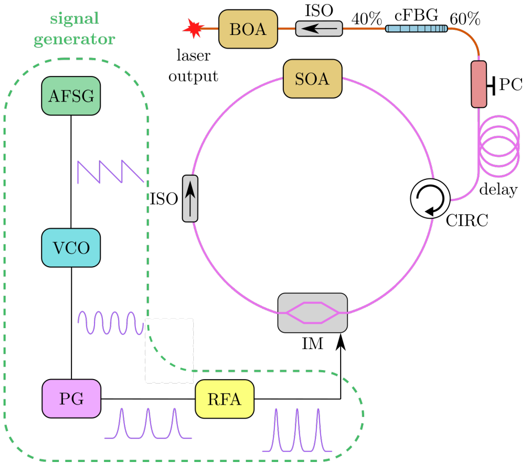


Figure 1: AKSS at 1060 nm. SOA - semiconductor optical amplifier, ISO - optical isolator, CIRC - optical circulator, cFBG - chirped fiber Bragg grating, PC - polarization controller, IM - fiber Mach-Zehnder intensity modulator, PMF - polarization maintaining fiber, FC - fiber coupler, BOA - booster amplifier, AFSG - arbitrary function signal generator, VCO - voltage-controlled oscillator, PG - pulse generator, RFA - RF amplifier.

The wavelength dependence of f_r in (1) is due to the chromatic dispersion in the laser cavity. By changing the modulation frequency over interval Δf_m the lasing wavelength is being swept over the range $\Delta\lambda$ proportionally

$$\Delta\lambda \approx S\Delta f_m, \tag{2}$$

where the tuning sensitivity S in general depends on the length and effective dispersion in the cavity. The lasing regime when only the resonant condition (1) is applied to the cavity shall be referred as the *single resonance sweeping regime*.[6,9]

To initiate *dual resonance sweeping operation* or *regime*, modulation frequency f_m is swept across many multiplies m of the fundamental resonant frequency at a sweep frequency equal or very close to the resonant frequency $f_s \approx f_r(\lambda)$. The RF spectrum of the signal being applied to the IM is then in the form of a Dirac comb[10]

$$\widetilde{V}_{VCO}[f_m(\lambda)] \sim \sum_{p=(1-N_{RF})/2}^{(N_{RF}-1)/2} \delta[f_m(\lambda) - f_m(\lambda_0) - p\underbrace{(f_{s0} + \delta f_s)}_{f_s}], \tag{3}$$

where $\delta(x)$ is the Dirac distribution, N_{RF} is the number of RF components (see Fig. 2), $f_m(\lambda_0)$ is the central modulation frequency, $f_{s0} = f_r(\lambda_0)$ is the reference sweep frequency and δf_s is the frequency detuning from f_{s0}. An example of an experimentally recorded RF spectrum of the signal is displayed in Fig. 3.

For no detuning, when $\delta f_s = 0$, the RF comb in Fig. 2 consists of components $\ldots, f_{m0} - f_r(\lambda_0)$, f_{m0}, $f_{m0} + f_r(\lambda_0), \ldots$ made of multiples of the fundamental resonant frequency $f_r(\lambda_0)$ only. If this signal is applied to the modulator, any component of the RF comb determines the same single lasing wavelength λ_0 emitted. When $\delta f_s \neq 0$, the RF comb in Fig. 2 consists of components $\ldots, f_{m0} - f_r(\lambda_0) - \delta f_s$, f_{m0}, $f_{m0} + f_r(\lambda_0) + \delta f_s, \ldots$ made of multiples of different fundamental resonant frequencies $f_r(\lambda)$ and with repetition of $f_r(\lambda_0) + \delta f_s$. The RF components $f_m(\lambda)$ move from their original positions as given by nonzero δf_s. It can be shown that wavelength tuning range $\Delta\lambda$ in the dual resonance sweeping regime increases

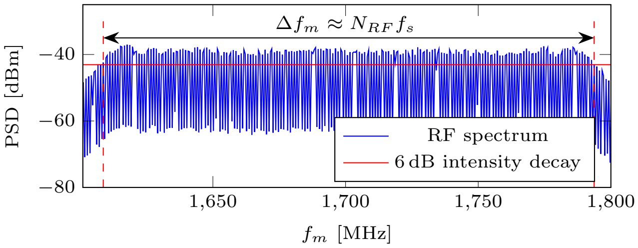


Figure 2: Experimentally recorded RF spectrum at the output of the VCO swept at $f_s \approx 912$ kHz over $\Delta f_m \doteq 185$ MHz with the number of frequency components $N_{RF} \gtrsim 200$. PSD - power spectral density.

approximately linearly with the detuning δf_s

$$\Delta\lambda(\delta f_s) = S_{dual}|\delta f_s|, \tag{4}$$

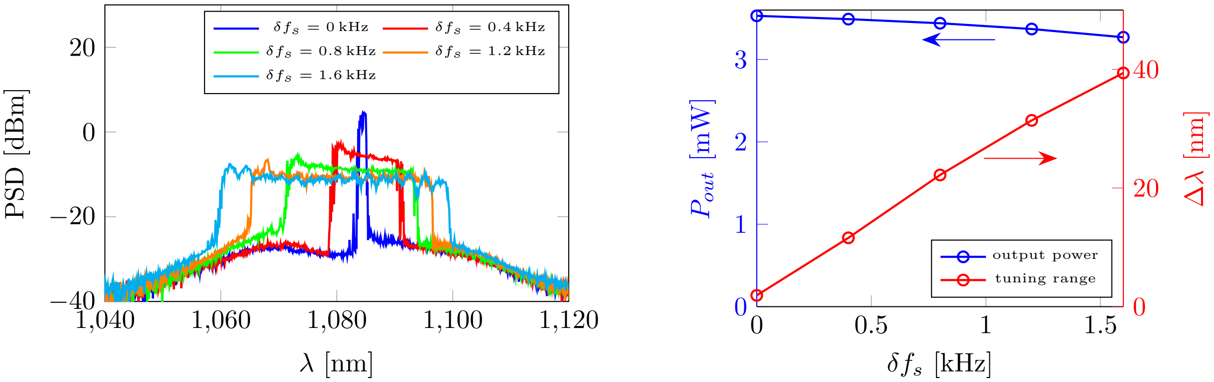
where S_{dual} is the wavelength tuning sensitivity in the dual resonance sweeping regime. In general, S_{dual} depends on dispersion in the cavity, cavity length and central modulation frequency f_{m0}.

There are several differences in the operation of the dual resonance regime and the conventional dispersion tuned AKSS (single resonance sweeping regime).[6,9] There is a common effort to have a fiber cavity as short as possible in the single resonance regime, while cavity length L in the dual resonance regime is in orders of $\sim 100\,\mathrm{m}$ and the sweep frequency f_s approximately equals resonance frequency $f_r = nL/c$, where n and c is fiber refraction index and speed of light, respectively. The essential difference between the regimes is in the principle how the wavelength sweep in the cavity is stored. As the time t progresses, at each moment, in the single resonance regime, only one lasing wavelength is contained in the cavity. In the dual resonance regime, at each moment, the whole wavelength sweep is contained in the cavity making it FDML-like fully akinetic swept source.

Similarly to a tunable FP filter in the FDML,[3] the IM in Fig. 1 in the dual resonance regime acts as a spectral filter and the most striking resemblance of the dual resonance regime with the FDML operation is that the entire wavelength sweep is optically stored within the laser cavity. However, there are several differences. Unlike the FDML operation, (i), the dual resonance regime is fully akinetic, (ii), the output is a train of short pulses with a repetition rate determined by the IM (GHz) with tuned wavelength, (iii), the modulation frequency is slightly detuned from the inverse of the roundtrip time and (iv), the cavity is dispersive.

3. RESULTS

The obtained preliminary peak-hold spectra and output power values (without a BOA) employing the dual resonance sweeping regime are displayed in Fig. 3. It has been achieved tuning range of $\approx 40\,\mathrm{nm}$ in Fig. 3(a) at a sweep frequency of $\approx 1.7\,\mathrm{MHz}$ with a slow decay in the output power with wider wavelength tuning ranges (see Fig. 3(b)).



(a) (b)

Figure 3: **(a)** Measured spectra and **(b)** output power (left axis) and tuning ranges (right axis) employing the dual resonance sweeping regime at 1060 nm.

4. CONCLUSION

The feasibility of employing the dual resonance sweeping regime in dispersion tuned AKSS at 1060 nm using an intensity modulator is presented. We also presented here analogies with a conventional dispersion tuned AKSS and FDML operation. A tuning bandwidth of 40 nm at a sweep rate of $\approx 1.7\,\mathrm{MHz}$ has been achieved. Further research is in progress to obtain first OCT images using the dual resonance sweeping regime in a dispersion tuned AKSS.

REFERENCES

[1] Fujimoto, J. and Drexler, W., [*Optical Coherence Tomography: Technology and Applications*], Springer Berlin Heidelberg, Berlin, Heidelberg (2008).

[2] Klein, T. and Huber, R., "High-speed oct light sources and systems," *Biomed. Opt. Express* **8**(2), 828–859 (2017).

[3] Huber, R., Wojtkowski, M., and Fujimoto, J. G., "Fourier domain mode locking (fdml): A new laser operating regime and applications for optical coherence tomography," *Opt. Express* **14**(8), 3225–3237 (2006).

[4] Lee, S.-W., Song, H.-W., Jung, M.-Y., and Kim, S.-H., "Wide tuning range wavelength-swept laser with a single soa at 1020 nm for ultrahigh resolution fourier-domain optical coherence tomography," *Opt. Express* **19**(22), 21227–21237 (2011).

[5] Tsai, T.-Y., Chen, T.-H., Chen, H.-K., Chueh, C.-B., Ellafi, D., Chase, C., Kuo, H.-C., Tsai, M.-T., Huang, M. C. Y., and Lee, H.-C., "High-speed optical coherence tomography imaging with a tunable HCG-VCSEL light source at the 1060 nm wavelength window," *SPIE* **12020**, 92 – 97 (2022).

[6] Lee, H. D., Kim, G. H., Shin, J. G., Lee, B., Kim, C.-S., and Eom, T. J., "Akinetic swept-source optical coherence tomography based on a pulse-modulated active mode locking fiber laser for human retinal imaging," *Sci Rep* **8**, 17660 (2018).

[7] Riha, R., Bradu, A., and Podoleanu, A., "Dual resonance akinetic dispersive cavity swept source at 900 khz using a cfbg and an intensity modulator," *Opt. Lett.* **47**(16), 4032–4035 (2022).

[8] Stancu, R. F. and Podoleanu, A. G., "Dual-mode-locking mechanism for an akinetic dispersive ring cavity swept source," *Opt. Lett.* **40**(7), 1322–1325 (2015).

[9] Yamashita, S. and Takubo, Y. W., "Wide and fast wavelength-swept fiber lasers based on dispersion tuning and their application to optical coherence tomography," *Photonic Sens.* **3**, 320–331 (2013).

[10] Haykin, S., [*Communication Systems*], Wiley Publishing, 4th ed. (2009).