A dual resonance sweeping regime in dispersion tuned akinetic swept source at 1550 nm

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ABSTRACT

In this summary, a fully akinetic FDML-like or so-called dual resonance sweeping regime, for swept source optical coherence tomography, SS-OCT, at 1550 nm is demonstrated. Instead of modulating the optical amplifier gain reported in our previous studies, here we employ a fiber intensity modulator as a mode-locking element. A chirped fiber Bragg grating is used to provide sufficient dispersion in the laser cavity. A tuning range of 25 nm is obtained for a sweep frequency of ≈ 900 kHz with a 6 dB drop-off in sensitivity at 2.6 mm optical path difference. Similarities in operation with the FDML concept are presented.

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 fiber lasers have also been reported.[6]

We here report a dispersion tuned AKSS operating in the dual resonance sweeping regime. By employing this 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 AKSS researched is depicted in Fig. 2(a).[7] The source uses a semiconductor optical amplifier, SOA, as a gain medium and a chirped fiber Bragg grating, cFBG, as a dispersive element. The operation of the AKSS is based on mode-locking of the optical field in the cavity. Mode-locking is achieved by modulating a fiber Mach-Zehnder intensity modulator, IM, in the cavity. To maximize transmission in the cavity, inline polarization controllers (PC) are employed. An optical circulator, CIRC, conveys the light to a chirped fiber Bragg grating. The optical isolator (ISO) together with the CIRC ensure unidirectional lasing in the laser cavity. The total cavity round trip length of $L \approx 226$ m determines a resonant frequency of $\overline{f}_r \doteq 912$ kHz. Output light is extracted via a directional coupler (DC) with 80% of power reinjected into the cavity. After isolation, laser cavity output is amplified with a booster amplifier, BOA.

A schematic diagram of the electronic circuitry driving the IM is detailed in Fig. 2(a) as well (inside the green dashed rectangle). A voltage-controlled oscillator, VCO, is driven by a ramp signal from an arbitrary function signal generator, AFSG, through an in bias-tee. The VCO output signal is amplified by a radio frequency (RF) amplifier, RFA, and then applied to the intensity modulator via another bias-tee. The operating point of the modulator is controlled separately by DC voltage from a regulated power supply, PS.

For the AKSS characterization, the laser is connected to an interferometer as shown in Fig. 2(b). The interferometer consists of two couplers with recirculation of the reference wave to avoid light being directed back into the optical source, terminated with a balanced photodetector, bPhD. The signal from the bPhD was observed on an RF spectrum analyzer, RFSA, and oscilloscope, OSC.

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:

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

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 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*.[6,8]

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 resonant frequency of the cavity f_r. The operation principle of the dual resonance regime can be described within frequency modulation (FM) framework. An FM signal is applied to the IM to induce mode-locking. The FM signal in Fig. 2(a) is generated at the VCO output by applying periodic signal $v(f_s t)$ with the frequency f_s, the sweep frequency, to its input. The instantaneous signal $V(t)$ being applied to the IM can be then written as[9]

$$V(t) \sim \sin\left[2\pi K_{VCO}\left(V_{DC}t + \int_0^t V_{AC}(f_s t')\mathrm{d}t'\right)\right], \tag{3}$$

where K_{VCO} is the voltage-to-frequency gain of the VCO, $f_{m0} = K_{VCO}V_{DC}$ is the carrier frequency and $V_{AC}(f_s t')$ is the AC voltage being applied to the VCO (see 2(a)). The RF spectrum $\widetilde{V}[f_m(\lambda)]$ of the signal $V(t)$ is then in the form of a Dirac comb

$$\widetilde{V}[f_m(\lambda)] \sim \sum_{p=(1-N_{RF})/2}^{(N_{RF}-1)/2} \delta[f_m(\lambda) - f_m(\lambda_0) - p\underbrace{(f_{s0} + \delta f_s)}_{f_s}], \tag{4}$$

where $\delta(x)$ is the Dirac distribution, N_{RF} is the number of RF components (see Fig. 1), $f_m(\lambda_0)$ 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. 1 consists of components $\dots, f_{m0} - f_r(\lambda_0), f_{m0}, f_{m0} + f_r(\lambda_0), \dots$ 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. 1 consists of components $\dots, f_{m0} - f_r(\lambda_0) - \delta f_s$, f_{m0}, $f_{m0} + f_r(\lambda_0) + \delta f_s, \dots$ 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 approximately linearly with the detuning δf_s

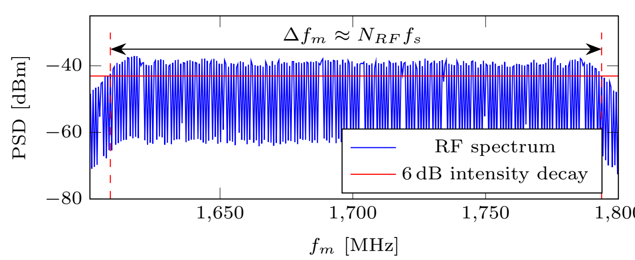
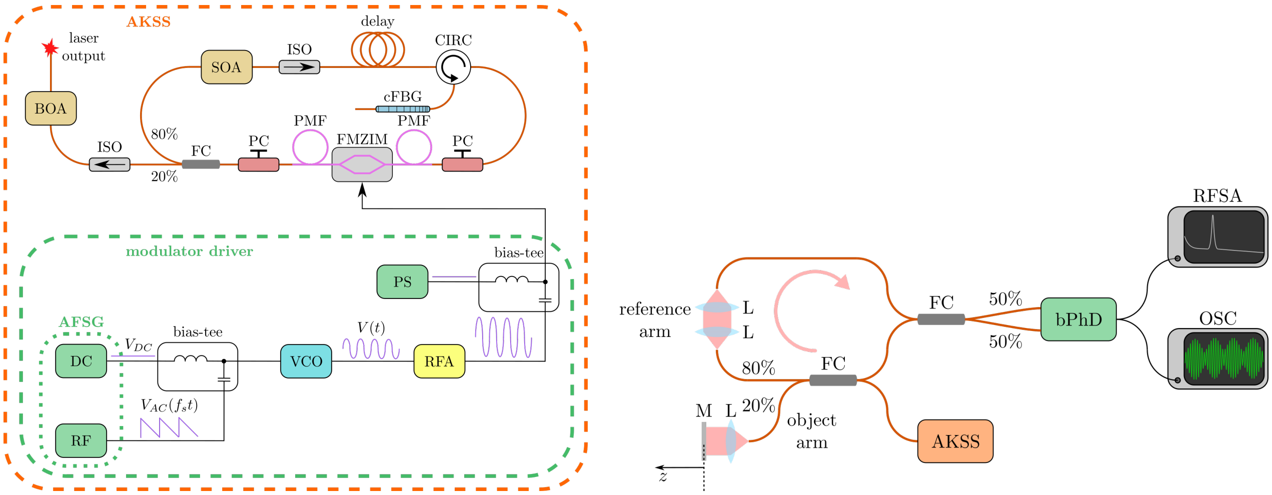


Figure 1: Experimentally recorded RF spectrum at the output of the VCO being swept at $f_s \approx 912\,\mathrm{kHz}$ over $\Delta f_m \doteq 185\,\mathrm{MHz}$ with the number of frequency components $N_{RF} \gtrsim 200$. PSD - power spectral density.

$$\Delta\lambda(\delta f_s) = S_{dual}|\delta f_s|, \tag{5}$$

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}.

Similarly to a tunable FP filter in the FDML,[3] the IM 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 an entire frequency sweep is optically stored within the laser cavity (2(a)). 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 repetition determined by the IM (GHz) with the tuned optical frequency, (iii), the modulation frequency is slightly detuned from the inverse of the roundtrip time and (iv), the cavity is dispersive.



(a) (b)

Figure 2: **(a)** AKSS at 1550 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, RFA - RF amplifier, PS - power supply. **(b)** SS-OCT sytem used for characterization of the AKSS setup. L - launcher lens system, M - mirror, bPhD - balanced photodetector, RFSA - RF spectrum analyzer, OSC - oscilloscope.

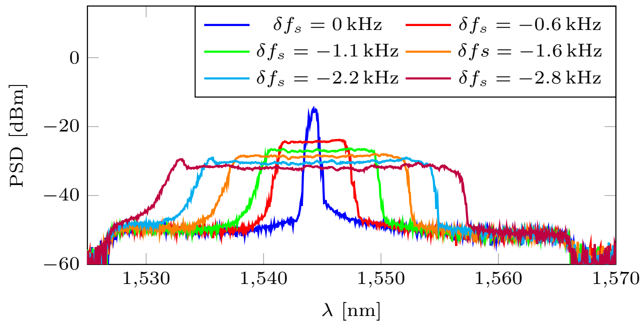
3. RESULTS

The optical peak-hold spectra obtained without the BOA for different values of the detuning frequencies δf_s from 912 kHz are shown in Fig. 3(a). After employing the BOA, the roll-off measurements are obtained in Fig. 3(b) using the interferometer sketched in Fig. 2(b). For $\delta f_s = -1.6$ kHz, -2.2 kHz and -2.8 kHz, for which tuning ranges of 15 nm, 20 nm and 25 nm are achieved, respectively, the sensitivity versus optical path difference (OPD) decays within 2 mm range. An OCT signal sensitivity of 82 dB is obtained for the OPD value close to zero (calculated as $20\log(A_{OPD}/A_{floor})$, where A_{OPD} and A_{floor} represent peak amplitude and floor level, respectively, and where the floor level is measured when the object signal is obstructed.

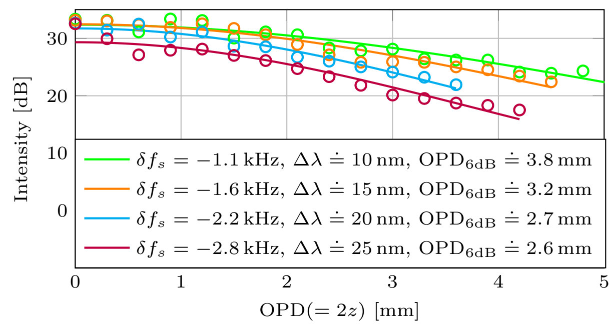
In order to measure the axial resolution, the method of master-slave interferometry is used. Axial point spread functions for different tuning ranges in Fig. 3(c) are produced at $z = 1$ mm. In Tab. 3(d), the measured axial resolution values δz at FWHM are compared with the theoretical $\delta z_{t\text{-}h} \approx 0.60\lambda^2/\Delta\lambda$ calculated for the top-hat optical spectral shape. The measured resolution values are in good agreement with the theoretical calculations.

4. CONCLUSION

The feasibility of employing the dual resonance sweeping regime in dispersion tuned AKSS for OCT at 1550 nm using an intensity modulator is presented. In addition to our study in,[7] we also present here analogies with FDML operation. A tuning bandwidth of 25 nm at a sweep rate of $\approx$ 900 kHz and a sensitivity decay with OPD of 2.6 mm at 6 dB are obtained.



(a)



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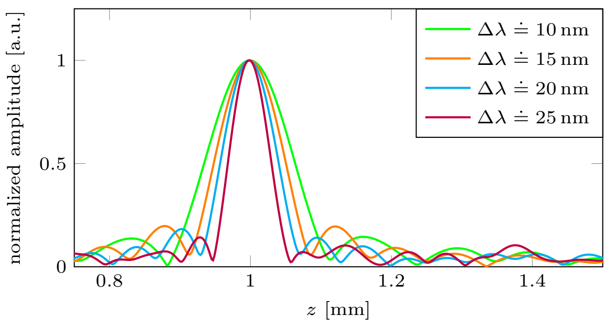

(c)

$\Delta\lambda$ [nm]	10	15	20	25
δz [mm]	0.13	0.10	0.08	0.06
$\delta z_{t\text{-}h}$ [mm]	0.14	0.10	0.07	0.06

(d)

Figure 3: AKSS characteristics. **(a)** Peak-hold spectra for different δf_s. **(b)** Sensitivity roll-off measurements for different δf_s ($\Delta\lambda$). **(c)** Axial point spread functions for different $\Delta\lambda$. **(d)** Comparison of the measured axial resolution FWHM values δz and theoretical calculations $\delta z_{t\text{-}h} \approx 0.60\lambda^2/\Delta\lambda$ for a top-hat optical spectral shape.

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