Travelling-Wave Modeling of Dynamics of Ultrafast Reflective-Intracavity-Filter Tunable Fabry-Pérot Lasers for Optical Coherence Tomography.

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Abstract: **Dynamics of Fabry-Pérot external-cavity laser diodes frequency-swept at a high rate using a tunable intracavity filter are investigated by travelling-wave modeling. The effect of filter properties and linewidth enhancement factor of the laser performance is assessed.**

I. INTRODUCTION AND BACKGROUND.

Tunable laser spectroscopy, or swept source Optical Coherence Tomography (OCT), is one of the widely used OCT methods [1]. It involves using a laser whose frequency is swept rapidly, at about 10 - 100 kHz periodic rate, across a wide wavelength range, about 100 nm, to measure the spectrum of interferences between tissue reflections and a reference reflector, which in turn is used to create a subsurface image of the tissue. The requirements to the laser source are as follows: (a) wide tuning range (~ 100 nm) for a high (< 15 μm) depth resolution of imaging; (b) fast tuning (100 kHz) for fast data acquisition (combined with the wide tuning range, this determines the speed of frequency sweeping of up to ~ 1 GHz/ns); and, finally, (c) a narrow dynamic linewidth (< 13 GHz) for a large imaging depth capability (although too narrow a linewidth is inadvisable too, in order to avoid artefacts). Thus, swept-source OCT typically uses external cavity laser diodes frequency-swept by means of a tunable intracavity filter. Ring lasers have been used previously [2]; however, the recent development of a highly frequency selective, compact reflecting filter [1,2] has allowed a simpler, more compact Fabry-Pérot construction to be used [1]. Since such a construction is relatively short (1-10 cm in length), the laser is frequency-swept through its intermodal frequency interval in only a few round-trips and thus operates in a perpetually transient regime. Depending on the combination of the filter bandwidth, the cavity intermodal interval and the sweeping speed, either near-single-mode hopping or quasi-continuous envelope tuning are possible. The tuning is strongly asymmetric, with the red tuning being more smooth and producing higher power output than the blue tuning. The output power decreases with tuning speed, and beyond a certain tuning speed, the laser does not switch on at all. Here, we use numerical modeling to relate the peculiarities of this dynamics to the laser parameters with a view to future construction optimisation.

II. THE MODEL. .

We use the travelling-wave laser model LasTiDom [4], applied previously to a number of constructions including mode-locked lasers and self-seeded gain-switched external cavity laser diodes. The gain chip is assumed to be a MQW semiconductor laser amplifier with typical parameters from the literature. The new feature in the model is account for the tunable frequency filter. We chose a Lorentzian approximation for the measured filter reflectance curve (Figure 1), which, with only a modest accuracy penalty compared to more accurate approximations, can be straightforwardly implemented in a digital filter [4], thus keeping the modelling fully in time domain.

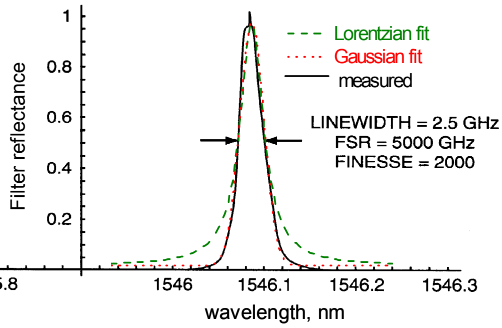

Figure 1. The measured [2] and approximated reflectance curves of the intracavity tunable filter.

II. RESULTS AND DISCUSSION .

We concentrate initially on the case of an external resonator with the intermodal interval ($\Delta\nu_{\mathrm{mod}}$=2.7 GHz) of the same order as the filter bandwidth ($\delta\nu_{filter}$=2 GHz). Then, in the steady state, with the filter tuned to one of the cavity modes (taken as the reference frequency of the model), CW single-mode output is simulated in agreement with experimental observations (Figures 2-3, left part of the graphs, $t<t_{start}$=20 ns). Under tuning, by sweeping the filter reflectance peak $\Delta\nu_{filter}$ at a constant rate $\Delta\nu_{filter} = \left(\frac{d\nu_{filter}}{dt}\right)(t-t_{start})$, an approximately periodically varying output is generated after an initial transient (Figure 2), as the laser is swept through cavity modes in turn (Figure 3). The period of these variations is $\Delta T = \Delta\nu_{\mathrm{mod}}\left(\frac{d\nu_{filter}}{dt}\right)^{-1}$. The average output power is noticeably lower at blue tuning than at red tuning. The origin of this asymmetry becomes clearer if we compare the power graph (Figure 2 a,b) with that of the corresponding instantaneous frequency $\Delta\nu = \frac{d}{dt}\arg(E_{out})$, E_{out} being the slow amplitude of the output light generated by the model (Figure 3).

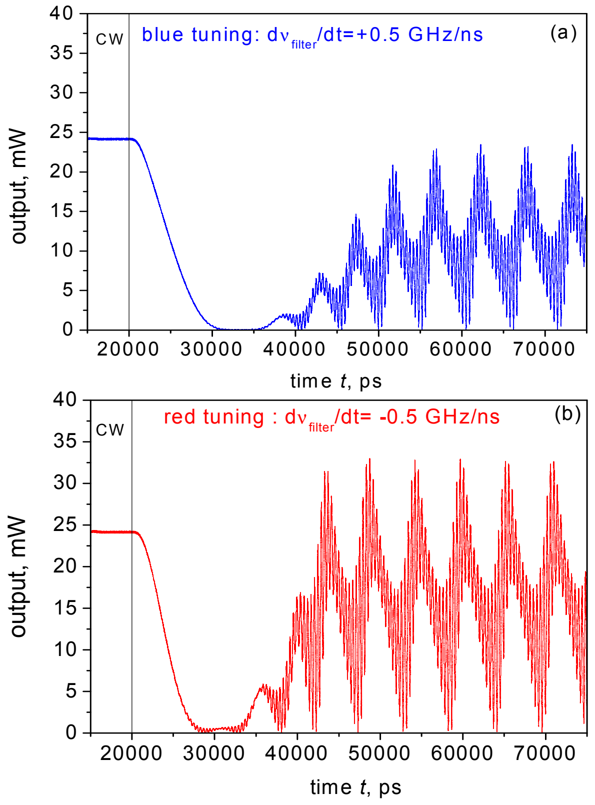

Figure 2. Transient power output of a swept source under blue (a) and red (b) tuning.

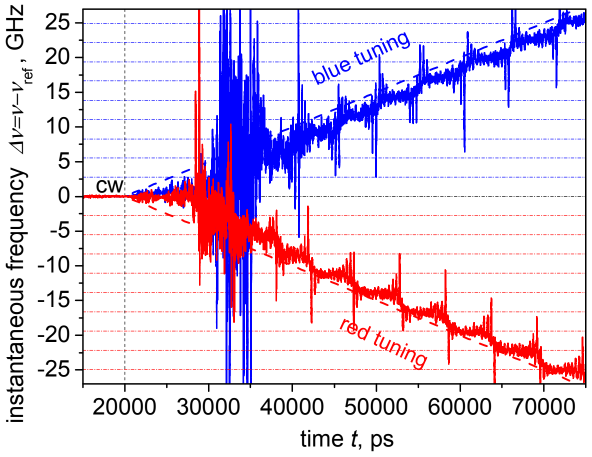

Figure 3. Time-resolved operating frequency of a swept source during the process of Figure 2 (filtered for clarity). Dashed lines: filter reflectance peak; horizontal dash-dotted lines: cavity modes.

Figure 3 clearly shows that, while the output during each intensity variation period of Figure 2 is never entirely single-mode at this high tuning rate, there is a dominant longitudinal mode during each such variation period. The tuning is in the form of mode hopping when the incumbent main mode becomes too far detuned from the reflectance peak and its intensity drops to a minimum value. The slower the tuning speed, the longer the inter-hop period ΔT and the nearer the laser behaviour between hops to true single-frequency operation. It is also seen that the process is more regular and, most importantly, the position of the dominant mode stays closer to the filter reflectance peak, in the case of red tuning than in the case of blue tuning; the latter is consistent with the asymmetric dependence of the average output power on the tuning speed. Figure 4 shows this dependence, demonstrating both the tuning asymmetry and the fall in intensity with the tuning speed. Above a certain critical tuning speed value, the laser does not switch on at all within the simulation span of 1 µs

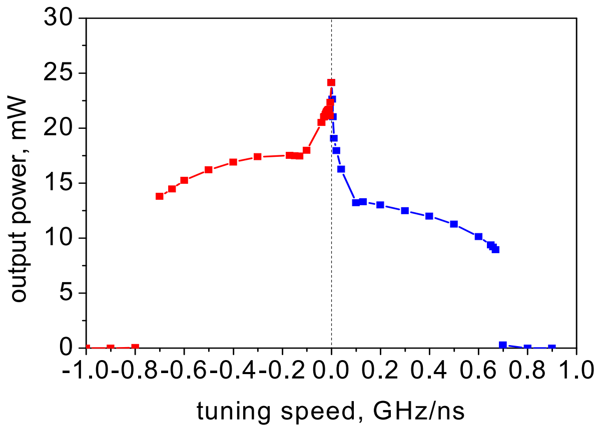

Figure 4. Tuning speed dependence of the average output power.

As in the case of ring lasers [2], the nature of this asymmetry is associated with the asymmetric mode interaction due to the nonzero linewidth enhancement factor α_H in the laser (the Bogatov effect) [5]. The curves above have been calculated with $\alpha_H=2$; we found that with $\alpha_H=0$, the tuning did indeed become symmetric. The use of nanostructure (e.g. quantum dot or dash) lasers, or of multisection lasers which can have lower effective linewidth enhancement factors, is thus promising; further work is now in progress.

IV REFERENCES.

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