Simulation of Swept Source External Cavity Lasers

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***Abstract*-We present a quasi-static model for the accurate simulation of swept source external cavity lasers. The model is based on steady-state solutions of multi-mode rate equations. The wavelength sweep is incorporated in the model by a spectral slicing technique. A comparison with experimental results demonstrates the usefulness of our approach. Limitations for the simulation of high-speed swept sources arising from the quasi-static approach presented here are discussed. Our model is a first step towards a time-dependent model that contains a full dynamic description of all relevant nonlinear effects.**

I. INTRODUCTION

Biomedical imaging applications like optical coherence tomography (OCT), spectroscopy or sensor applications require a light source that provides fast (1-200 kHz) wavelength-tunability over a wide wavelength range (100-150 nm) with a narrow instantaneous linewidth (20-100 pm). For imaging applications like OCT, this narrow linewidth translates into a coherence length of several millimeters (5-25 mm), which then defines the imaging depth. In order to address this wide range of applications, these so-called swept sources are needed at various wavelengths in the near-infrared (NIR) wavelength range, for example at 840 nm, 1060 nm, 1220 nm, 1310 nm, 1550 nm or other wavelengths.

A preferred type of light source for those swept sources is therefore free-space external cavity lasers (ECLs) with semiconductor optical amplifiers (SOAs), realized in a flexible free-space laser architecture with micro-optical components that allow for great wavelength flexibility [1]. The flexibility and the need for customizing such ECLs to a particular application or to a particular customer requires an advanced simulation tool to properly engineer such swept sources and to evaluate architectural modifications prior to realizing them as prototype modules. However, such simulation tool needs to properly cover aspects like small-signal and large-signal amplification of optical signals inside the gain cavity including nonlinear gain saturation, broad spectral gain bandwidth and its compression due to saturation effects as well as other nonlinear effects like self-phase modulation in order to describe limitations that may occur for ultra-fast sources that sweep across 100-150 nm within 5-10 microseconds.

In this paper we present a quasi-static model that describes most of the relevant properties of a swept source ECL very accurately. The model is particularly useful for swept sources operating with tuning frequencies up to 20-40 kHz. For higher sweep frequencies some details of the output characteristics are determined by dynamic effects, which cannot be covered by a quasi-static model. This requires an extension to a full dynamic version of the model presented here.

II. SWEPT SOURCE ARCHITECTURE

Our swept sources are realized as external cavity lasers with a Littrow configuration, featuring a high-performance ultra-broadband SOA that provides a 10-dB gain bandwidth of more than 150 nm at 1310 nm, for example. The SOAs are optimized for a single polarization (TE) and for high linearity over a wide input power range. Moreover, they are designed according to the guidelines given in [2] for the avoidance of any disturbing residual facet reflection. The light in and out of the SOA chip is collimated with micro-optical lenses and sent to a 1D micro-electro-mechanical system (MEMS) mirror that deflects the light onto a proprietary high-performance diffraction grating. An optical output coupler provides sufficient feedback for the laser cavity to operate as well as sufficient light output that is coupled into a single-mode fiber. The complete ECL is realized on a temperature-controlled optical bench and is packaged inside a 26-pin butterfly package, as shown in Fig. 1.

The mono-crystalline silicon MEMS mirrors are high-performance, electro-static and resonant devices that provide long-term scanning operation without fatigue or any degra dation. They are operated in their mechanical resonance at10, 25, 50 or 100 kHz, for example, driven with a high-voltage (50- 220 V) low-jitter clock signal. The *Q*-factor of the MEMS mirror is relatively high (500-1000), which means that the scanner is performing a sinusoidal harmonic oscillation in its

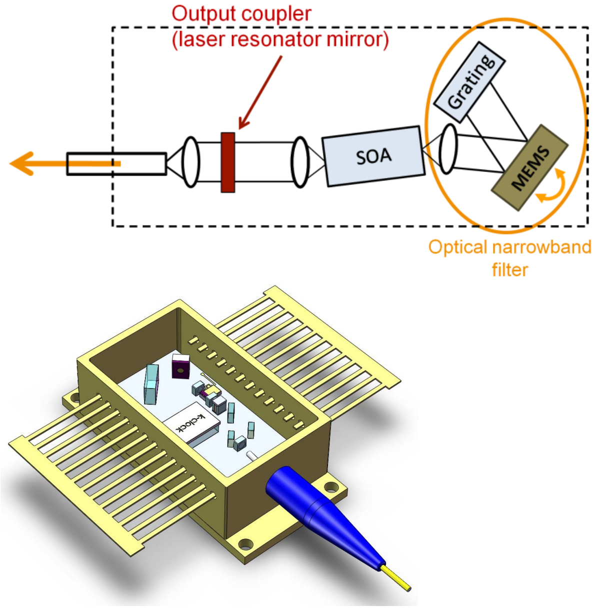

Fig. 1. Schematic view of a free-space Littrow external laser architecture with an SOA, a MEMS scanner and a diffraction grating that is realized in a miniature optical butterfly package with a single-mode fiber output.

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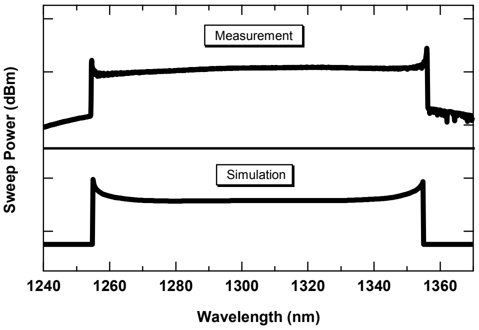

Fig. 2. Measured (upper plot) and simulated (lower plot) optical spectrum of a 1310-nm swept source operating at 40 kHz sweep frequency.

resonance. The sinusoidal movement implies that the MEMS mirror slows downs and turns around at the edges of the sweep spectrum, resulting typically in a rectangular sweep spectrum, as shown in Fig. 2.

III. MODELING OF SWEPT SOURCE CHARACTERISTICS

We model the laser cavity shown in Fig. 1 by using the approach presented in [3] but properly adapted to the requirements of a swept source. The gain chip is described by a set of multi-mode rate equations for the photon density of each external cavity mode and one equation for the carrier density. The feedback from the external elements is taken into account by effective front-side and back-side reflectivity values. These values are strongly wavelength dependent because of the narrowband spectral filter characteristic of the grating and the MEMS mirror.

The sinusoidal modulation of the MEMS with time results in a periodic sweep of the wavelength spectrum. Thus, each time interval corresponds to a certain wavelength interval and vice versa. The wavelength sweep is incorporated into the model by slicing the whole wavelength range into intervals $\Delta\lambda_i \sim 1$ nm, which are small compared to the entire tuning range (~100 nm) but large compared to the effective filter width (~100 pm) . The filter width itself is broad compared to the Fabry-Perot mode spacing of the external cavity modes, which is between 5 pm and 15 pm for a typical swept source laser with length between 50 mm and 150 mm.

Then the quasi-static behavior of the system is found by solving the set of rate equations for each interval $\Delta\lambda_i$ under steady-state condition. The resulting output power is weighted by the time interval Δt_i, which corresponds to the wavelength interval $\Delta\lambda_i$. Adding the weighted solutions for each slice is representative for what is observed in the experiment as a spectrally resolved time-averaged quantity.

The quality of the model is demonstrated by a comparison of simulation results with measurements either obtained for sweep operation with a tuning frequency of 40 kHz (Fig. 2) or for cw operation without wavelength tuning (Fig. 3). For the cw measurement the MEMS mirror position is fixed so that the laser's emission spectrum is kept constant around 1305 nm. Obviously, the model does not only reproduce the laser's *L-I* characteristic very accurately (a), but also other important quantities like the optical signal-to-noise ratio (OSNR) as function of the SOA drive current, (b) or details of the emission spectrum (c). The OSNR of a swept source laser is directly related to its coherence length, which is a key parameter in swept source laser applications.

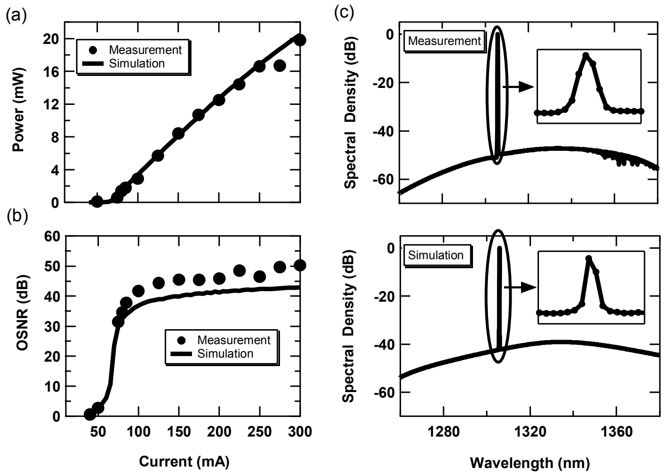

Fig. 3. Comparison between measurement and simulation results for a swept source ECL in cw operation. (a) Fiber-coupled output power, (b) optical signal-to-noise ratio (OSNR), and (c) emission spectrum recorded with a resolution of 0.1 nm at an SOA drive current of 300 mA.

As can be clearly seen from Fig. 2, the model reproduces the typical rectangular-shaped sweep spectrum with an overemphasized amount of power at the edges very well. These peaks are caused by the slow-down of the MEMS mirror around its turning points.

IV. SUMMARY

We have presented a quasi-static model for the accurate description of the swept source ECL's output characteristics. The model can be used as an optimization tool for the swept source architecture with respect to output power, OSNR, and other important parameters. Most of the simulation results are still valid for high-speed swept sources operating at frequencies above 40 kHz, although the quasi-static approach presented here might be questionable. The correct description of some details in the output characteristics of such fast swept sources requires the inclusion of all relevant nonlinear dynamic effects into the model. Our model can be considered as the first step towards a full dynamic model in the time domain.

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